EXAMINATION OF THE IGNITABILITY CHARACTERISTICS OF COAL DUST/AIR AND METHANE/COAL DUST/AIR MIXTURES

FINAL REPORT

BY

P.R. Amyotte, M.J. Pegg and Y.H. Sun

Department of Chemical Engineering
Technical University of Nova Scotia (TUNS)
P.O. Box 1000
Halifax, Nova Scotia
Canada B3J 2X4

Work on this project was conducted under the auspices of the
Department of Energy, Mines and Resources

94 pp

March, 1991

DSS FILE NUMBER: 058SS.23440-9-9200
DSS CONTRACT NUMBER: 23440-9-9200/01-SS
EMR SCIENTIFIC AUTHORITY: Dr. K.J. Mintz

MICROMEDIA

EXECUTIVE SUMMARY

An experimental investigation of coal dust explosions has been conducted in a 26-L, spherical chamber. Channel samples of coal from the Prince and Phalen mines of the Cape Breton Development Corporation were used. The overall objective of the work was to investigate the ignitability characteristics of the coals, alone and also with admixed methane. Tests were also conducted to examine the relative effectiveness of various rock dusts (limestone, dolomite and magnesite) with respect to the inerting of coal dust explosions.

Two size fractions were produced for each of the Prince and Phalen coals. For each coal type, particle size, methane concentration (0% and 2%), and ignition energy (generally ranging from 50 J to 10 kJ), tests were conducted at different coal dust concentrations to establish the lean flammability limit. In the portion of the study dealing with inerting requirements, tests were conducted for each rock dust with the smaller size fraction of Prince coal, a coal dust concentration of 0.5 kg/m^3, an ignition energy of 5 kJ, and no methane present. Rock dust concentrations ranged from 20% of the total solids mixture to the percentage required to suppress an explosion.

The apparent lean flammability limit of the coal dust/air mixtures was observed to decrease with increasing ignition energy. The decrease was rapid at low energies, with an approach to an asymptotic value of the lean limit at high energies. A stored ignition energy of 5 kJ was required to measure these asymptotic values which represent the true lean flammability limit. The apparent lean limit at a given ignition energy was found to decrease in the presence of methane, with a reduction in mass mean diameter of the parent coal, and with an increase in coal volatile content. These three conditions also lead to an enhancement of the ignitability of the coal dust/air mixtures, meaning that ignition of a given coal dust concentration was possible with lower energies. The lowering of the lean limit with methane admixture, particle size reduction and increase in volatiles was more pronounced at lower ignition energies.

The explosion inerting data showed that limestone, dolomite and magnesite appear to be of similar effectiveness for explosion suppression. The particle size of a particular rock dust was observed to have a significant effect on the amount required for inerting, with finer size rock dusts being more effective. It must be emphasized that limited inerting tests were conducted; this is an area where further work is recommended.

SOMMAIRE EXECUTIF

Une investigation expérimentale sur les explosions de poussière du charbon a été conduite dans une chambre sphérique d'une capacité de 26 litres. Le charbon utilisé a été acquis des deux mines, Prince et Phalen, gérées par la Société du Développement du Cap Bréton. L'objectif d'ensemble de ce travail a été d'étudier le comportement explosif de ces deux variétés de charbon sans ou avec un mélange de methane. Les épreuves ont aussi été éffectuées sur la quantité nécessaire d'une variété de poussières rochées (dolomite, calcaire et magnésite) en vue de rendre ces coups de poussière de charbon inerte.

Des particules de deux grandeurs ont été utilisées pour chaque échantillon du charbon originant des mines Prince et Phalen. Les épreuves ont été conduites sur les concentrations de poussière du charbon pour établir la limite maigre de l'inflammabilité pour chaque variété, grandeur de particule, concentration de méthane (0% et 2%) et d'énergie d'ignition (généralement de 50J à 10KJ). Dans la partie de l'étude qui s'occupe des conditions réquises pour rendre inerte, des épreuves ont été conduites pour chaque poussière rochée avec la plus petite partie de taille du charbon Prince, une concentration de poussière de 0.5 kg/m^3, une énergie d'ignition de 5kJ et sans méthane. Les concentrations de poussière rochée variaient de 20% du mélange totale des particules solides jusqu'à le pourcentage requis pour étouffer une explosion.

Il a été observé que la limite maigre de l'inflammabilité diminue avec l'augmentation de l'énergie d'ignition. Cette diminution était rapide à basse énergie, approchant une valeur asymptotique de la limite maigre de l'inflammabilité. À une énergie d'ignition donnée, la limite maigre d'inflammabilité evidente diminue en présence de méthane, avec la reduction de diamètre masse moyen du charbon parent et avec une augmentation dans le contenu volatil du charbon. Ces trois conditions mènent renchérissement à l'allumage des mélanges air/poussière du charbon, voulant dire que l'ignition d'une concentration de poussière de charbon est possible aux énergies abaissées. En abaissant la limite maigre avec mélange de méthane, la réduction de la grandeur des particules et l'augmentation des volatils étaient plus marqués aux énergies d'ignition abaissées.

L'information sur la suppression de l'explosion a demontré que la calcaire, le dolomite et le magnésite semblent avoir un même effet sur la suppression de l'explosion. Il a été observé que la grandeur de particule de la poussière rochée a fortement influencé le montant necessaire pour l'inertement; la plus fin poussière rochée étant plus effective. Il faut attirer l'attention sur le fait que le nombre d'épreuves d'inertion était limité; plus d'investigation dans ce domaine est recommandé.

TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		i
SOMMAIRE EXECUTIF		iii
LIST OF TABLES		vii
LIST OF FIGURES		viii
ACKNOWLEDGEMENTS		xi
CHAPTER 1	INTRODUCTION	1
	1.1 Scope and Objectives of Present Work	1
	1.2 Coal Dust Explosion Hazard	2
	1.3 Ignition Scenarios	4
	1.4 Explosion Inerting	5
CHAPTER 2	EXPERIMENTAL	6
	2.1 Coal Dust	6
	2.2 Rock Dust	10
	2.3 Experimental Program	10
	2.4 Apparatus and Procedure	15
	2.4.1 Methane tests	15
	2.4.2 Inerting tests	17
	2.4.3 Chemical ignitors	17
	2.4.4 Electric matches	19
	2.4.5 Data acquisition and analysis	19
	2.4.6 Spark tests	21
CHAPTER 3	RESULTS	22
CHAPTER 4	DISCUSSION	36
	4.1 Relationship to Previous Work	36
	4.2 Lean Flammability Limit: Definition and Criteria	36
	4.3 Effect of Ignition Energy on Lean Flammability Limit	37
	4.4 Stored and Effective Energies	41
	4.5 Spark Tests	44
	4.6 Ignition Source Geometry	46
	4.7 Effect of Methane Admixture on Lean Flammability Limit	46
	4.8 Increased Hazard Due to Co-Presence of Methane and Coal Dust	52
	4.9 Effect of Coal Particle Size on Lean Flammability Limit	57
	4.10 Effect of Coal Volatile Content on Lean Flammability Limit	62
	4.11 Inerting Tests	67
	4.11.1 Effect of rock dust type	69
	4.11.2 Effect of rock dust particle size	73

		Page
4.12	Applicability to Coal Mining Industry	73
4.12.1	Turbulence level	73
4.12.2	Methane concentration	76
4.12.3	Ignition source and energy	76
4.12.4	Coal particle size	77
4.12.5	Coal ash content	77
CHAPTER 5	CONCLUSIONS AND RECOMMENDATIONS	78
5.1	Summary of Conclusions	78
5.2	Recommendations for Further Work	79
REFERENCES		81

LIST OF TABLES

		Page
Table 2.1	Particle size analyses of coals.	8
Table 2.2	Proximate analyses of coals.	9
Table 2.3	Particle size analyses of rock dusts.	12
Table 2.4	Compositional analyses of rock dusts.	13
Table 2.5	Test matrix for coal dust/air and methane/coal dust/air ignitability experiments.	14
Table 3.1	Results of tests conducted with stored spark energy of 16.2 J.	31
Table 4.1	Comparison of products of lean flammability limit and coal volatile content (for a given particle size and methane concentration).	68
Table 4.2	Rock dust inerting requirements for Prince 2 coal (0% methane, 5-kJ ignition energy).	70

LIST OF FIGURES

		Page
Fig. 1.1	Histograms showing incidents and fatalities in Nova Scotia coal mines on a bimonthly basis (1900 to present day).	3
Fig. 2.1	Sample coal particle size distribution (Prince 1) determined by Malvern Instruments (2600 Series) analyzer.	7
Fig. 2.2	Sample rock dust particle size distribution (limestone) determined by Malvern Instruments (2600 Series) analyzer.	11
Fig. 2.3	Schematic diagram of 26-L explosion vessel and auxiliary equipment.	16
Fig. 2.4	Relationship between mass of rock dust and rock dust percentage.	18
Fig. 2.5	Sample pressure-time trace.	20
Fig. 3.1	Apparent lean flammability limit as a function of stored ignition energy (Prince 1, 0% methane).	23
Fig. 3.2	Apparent lean flammability limit as a function of stored ignition energy (Prince 1, 2% methane).	24
Fig. 3.3	Apparent lean flammability limit as a function of stored ignition energy (Prince 2, 0% methane).	25
Fig. 3.4	Apparent lean flammability limit as a function of stored ignition energy (Prince 2, 2% methane).	26
Fig. 3.5	Apparent lean flammability limit as a function of stored ignition energy (Phalen 1, 0% methane).	27
Fig. 3.6	Apparent lean flammability limit as a function of stored ignition energy (Phalen 1, 2% methane).	28
Fig. 3.7	Apparent lean flammability limit as a function of stored ignition energy (Phalen 2, 0% methane).	29
Fig. 3.8	Apparent lean flammability limit as a function of stored ignition energy (Phalen 2, 2% methane).	30
Fig. 3.9	P_{max} and $(dP/dt)_{max}$ as a function of limestone concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).	32
Fig. 3.10	P_{max} and $(dP/dt)_{max}$ as a function of dolomite (regular grind) concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).	33

Page

Fig. 3.11	P_{max} and $(dP/dt)_{max}$ as a function of dolomite (-300 mesh) concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).	34
Fig. 3.12	P_{max} and $(dP/dt)_{max}$ as a function of magnesite concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).	35
Fig. 4.1	P_{max} and $(dP/dt)_{max}$ at various coal dust concentrations (Phalen 1, 0% methane, 1000-J ignition energy).	38
Fig. 4.2	P_{max} and $(dP/dt)_{max}$ at various coal dust concentrations (Prince 2, 0% methane, 250-J ignition energy).	39
Fig. 4.3	Relationship between pressure rise due to ignitor and stored ignition energy.	42
Fig. 4.4	Relationship between effective ignition energy and stored ignition energy.	43
Fig. 4.5	Effect of effective ignition energy on apparent lean flammability limit (Prince 2, 0% methane).	45
Fig. 4.6	Effect of methane admixture on apparent lean flammability limit of Prince 1 coal.	47
Fig. 4.7	Effect of methane admixture on apparent lean flammability limit of Prince 2 coal.	48
Fig. 4.8	Effect of methane admixture on apparent lean flammability limit of Phalen 1 coal.	49
Fig. 4.9	Effect of methane admixture on apparent lean flammability limit of Phalen 2 coal.	50
Fig. 4.10	Effect of methane admixture on lean flammability limits of Prince 1 coal (upper plot) and Prince 2 coal (lower plot) for ignition energy of 5 kJ.	53
Fig. 4.11	Effect of methane admixture on lean flammability limits of Phalen 1 coal (upper plot) and Phalen 2 coal (lower plot) for ignition energy of 5 kJ.	54
Fig. 4.12	Effect of methane admixture on lean flammability limits of Prince 2 coal (upper plot) and Phalen 2 coal (lower plot) for ignition energy of 138 J.	55
Fig. 4.13	Effect of coal particle size on apparent lean flammability limit of Prince coals (0% methane).	58
Fig. 4.14	Effect of coal particle size on apparent lean flammability limit of Prince coals (2% methane).	59

		Page
Fig. 4.15	Effect of coal particle size on apparent lean flammability limit of Phalen coals (0% methane).	60
Fig. 4.16	Effect of coal particle size on apparent lean flammability limit of Phalen coals (2% methane).	61
Fig. 4.17	Effect of coal volatile content on apparent lean flammability limit of larger particle size coals (0% methane).	63
Fig. 4.18	Effect of coal volatile content on apparent lean flammability limit of larger particle size coals (2% methane).	64
Fig. 4.19	Effect of coal volatile content on apparent lean flammability limit of smaller particle size coals (0% methane).	65
Fig. 4.20	Effect of coal volatile content on apparent lean flammability limit of smaller particle size coals (2% methane).	66
Fig. 4.21	Effect of rock dust type and concentration on P_{max} of Prince 2 coal (0% methane, 5-kJ ignition energy).	71
Fig. 4.22	Effect of rock dust type and concentration on $(dP/dt)_{max}$ of Prince 2 coal (0% methane, 5-kJ ignition energy).	72
Fig. 4.23	Effect of rock dust particle size and concentration on P_{max} of Prince 2 coal (0% methane, 5-kJ ignition energy).	74
Fig. 4.24	Effect of rock dust particle size and concentration on $(dP/dt)_{max}$ of Prince 2 coal (0% methane, 5-kJ ignition energy).	75

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the contributions of the following organizations and people: Energy, Mines and Resources (EMR) Canada, for funding the work; the Cape Breton Development Corporation (CBDC), for supplying the coal, limestone and dolomite; Canadian Refractories, for supplying the magnesite; Dr. K.J. Mintz (EMR) and Mr. J.C. Campbell (CBDC), for their scientific and technical insight; Dr. K.I. Wilkie (TUNS), for developing and maintaining the computerized system for dust dispersion and ignition and data acquisition; Mr. W. Sloan, Mr. A. Snow and Mr. D. Wadden (TUNS), for their help in preparing the experimental apparatus; Mr. R. Soundararajan (TUNS), for his help in performing the experiments; Ms. D. Laffin (TUNS), for typing the manuscript.

Chapter 1

INTRODUCTION

Many of the dusts found in industry are susceptible to the explosion hazard. Along with the more commonly quoted cases of coal and grain dust, one may include, for example, sugar, aluminum, polyethylene, benzoic acid and paper in a list of explosible dusts. The occurrence of dust explosions for these and other materials is well-documented. The recent text edited by Cashdollar and Hertzberg (1987) gives several case studies; among others, these include coal dust fire and explosion accidents in coal mines (Cashdollar et al., 1987) and in cement plants (Alameddin and Luzik, 1987), aluminum powder and flour explosions in the United Kingdom (Abrahamsen, 1987), and dust explosion incidents in grain handling facilities (Kauffman, 1987).

1.1 Scope and Objectives of Present Work

The scope of the present work is an investigation of small-scale, confined, deflagrative dust explosions. It is an experimental study, with the major piece of apparatus being a 26-L, spherical explosion chamber. The material examined was coal dust which was produced from channel (mine-face) coal from two Cape Breton Development Corporation (CBDC) mines (Prince and Phalen). Two size fractions were generated for each of the two coals.

The objectives of the present work are summarized as follows:

(1) to investigate the ignitability characteristics of the Prince and Phalen coals by examining the influence of ignition energy on the lean flammability limit;

(2) to investigate the effects of methane admixture on the ignitability characteristics of each of the coals; and

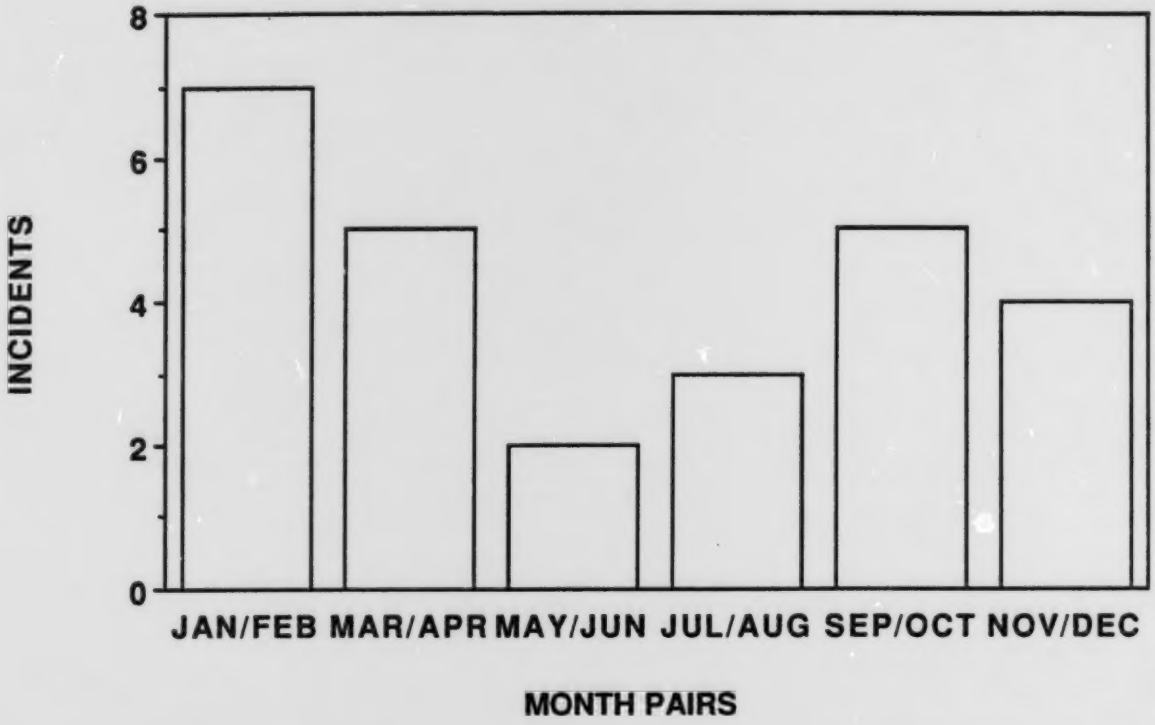
(3) to examine the relative effectiveness of limestone, dolomite and magnesite with respect to the inerting of coal dust explosions.

Rationale for each of these objectives is given in the following sections.

1.2 Coal Dust Explosion Hazard

In spite of significant research worldwide, the coal dust explosion hazard has not been eliminated. There have been serious explosion incidents in coal mines in Germany (June, 1988), Yugoslavia (August, 1990) and Czechoslovakia (October, 1990). Nagy (1981) reports that between 1880 and 1980, there were about 500 major gas and dust explosions in coal mines in the United States. There were also several thousand minor explosions and ignitions during this period; the number of fatalities from all these incidents exceeded 15,000. Nagy (1981) gives data which show that although the frequency and magnitude of mine explosions in the United States (and the number of related fatalities) have been decreasing since 1910, explosions continue to happen.

Since 1900 there have been 26 fires and/or explosions in Nova Scotia coal mines which resulted in 294 fatalities. There were a total of 1,850 fatalities in coal mines in the province throughout that time; 16% of coal mine fatalities since 1900 have thus been caused by fires or explosions. Figure 1.1 gives two histograms which illustrate these data. The upper plot shows that over the past century, mine explosions and fires in Nova Scotia have occurred with greater frequency in winter than in summer. This is consistent with experience in other geographical locations, and is attributed to a lower water content of the mine atmosphere and surfaces during the colder winter months (Nagy, 1981; Foniok, 1985). From a hazard evaluation perspective, the effects of a decrease in air humidity are numerous; most notable are an increase in the dispersibility of coal dust and decreases in inert content, lean flammability limit and minimum ignition energy of the dust. The lower plot in Fig. 1.1 demonstrates that there is not necessarily a correlation between number of incidents and number of fatalities. One mine explosion can have truly devestating consequences; the spike in the bar for July and August is due primarily to the explosion in the Dominion No. 12 mine in 1917.



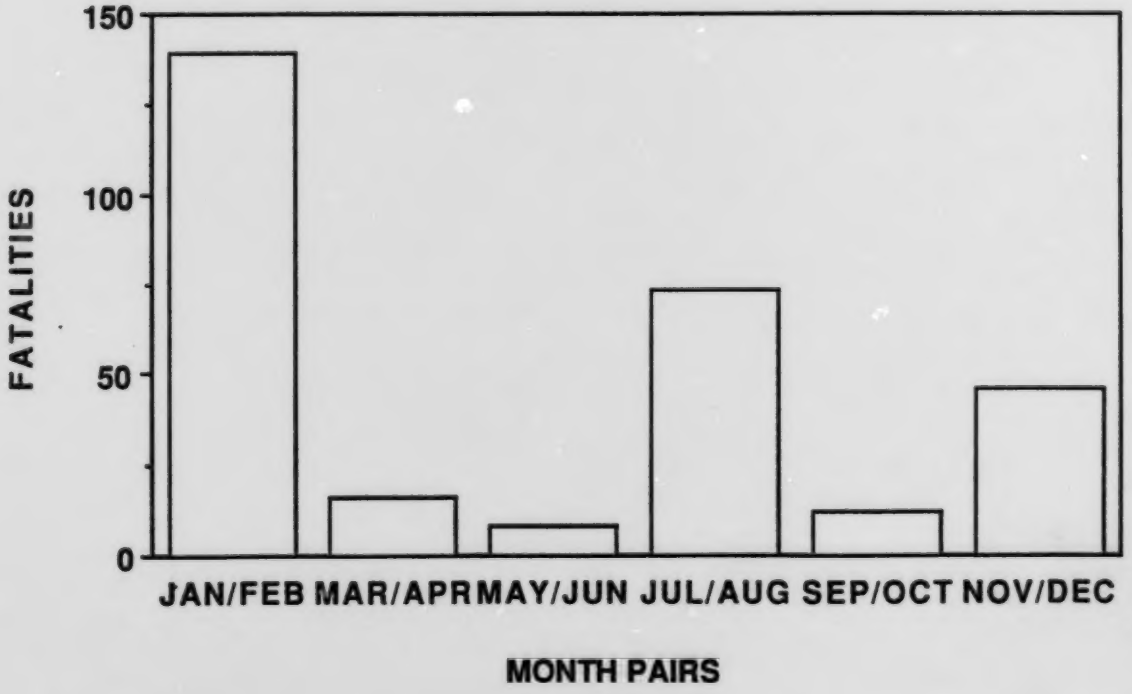


Fig. 1.1 Histograms showing incidents and fatalities in Nova Scotia coal mines on a bimonthly basis (1900 to present day).

1.3 Ignition Scenarios

An indication of the explosion hazard associated with coal dust can be gained by examining the steps leading to a fully developed mine explosion. These have been outlined by Hertzberg et al. (1982) as follows:

(1) Growth of a large, flammable methane/air zone near the face that is being mined, resulting from increasing methane emissions as the mining process advances into the fresh seam.

(2) Ignition of that flammable volume by some means.

(3) Development of a localized methane/air explosion (termed a *primary* explosion) and flame acceleration outward from the face.

(4) Lifting of coal dust accumulations by the flow generated ahead of the accelerating methane/air flame, and mixing of that dust with air to create a flammable coal dust/air mixture.

(5) Ignition of the dust/air mixture by the methane/air flame.

(6) Further turbulent acceleration of the dust flame front which lifts more coal dust, mixing it with air throughout an increasingly lengthening zone ahead of the flame.

(7) Propagation of a dust explosion (termed a *secondary* explosion) throughout the mine.

Methane ignition sources under item (2) include frictional and electrical sparks, flames, and explosives. Direct ignition of airborne coal dust is possible by relatively high energy flames and explosives; lower energy sparks are also capable of igniting a coal dust/air cloud providing the turbulence level in the cloud is not excessive (Amyotte et al., 1988). Avoidance of all potential ignition sources, therefore, is an integral part of an explosion prevention scheme in coal mining operations. Objectives (1) and (2) in section 1.1 were aimed at quantifying this requirement of ignition source avoidance.

1.4 Explosion Inerting

The term "inerting", as applied to the mining of coal is a somewhat generic description of the practice of adding inhibitors to coal dust. This inhibitor addition can be carried out in a responsive manner to arrest flame propagation, as in the case of rock dust or water barriers, where the contents of the barriers are dispersed by the pressure wave from an explosion. Alternatively, premixing by hand or machine of rock dust with deposited coal dust is an example of inhibitor addition in a preventive manner. When added in the correct proportion, rock dust premixed with coal dust removes one of the conditions necessary for deflagration initiation, namely an explosible solids mixture. This was the subject of objective (3) in section 1.1.

Government regulations in Canada, the United States and many other countries require the use of rock dust (usually limestone or dolomite) as the chief inerting agent in coal mines. As with water, limestone and dolomite are generally viewed as thermal inhibitors by virtue of their heat-sink action. Additionally, rock dusts are effective as flame arrestors because of their ability to be simultaneously dispersed with coal dust (Sapko et al., 1989). Chemical inhibitors such as salt and ammonium phosphate have also been used in some countries; for example, both on an experimental basis in the United States, and salt, through an encrustation or binding technique, in Germany. A good description of inerting requirements in coal mines, written from a practical point of view, has been given by Nagy (1981).

Chapter 2

EXPERIMENTAL

In this chapter, the materials and methods used to conduct the explosion tests are described.

2.1 Coal Dust

Channel (mine-face) samples of coal from the Prince and Phalen mines were obtained from CBDC. At TUNS, each coal was ground and sieved to produce two size fractions. There were thus four coal dust samples prepared for testing. They are referred to throughout this report as Prince 1 and Prince 2, and Phalen 1 and Phalen 2.

After grinding and sieving, each coal dust sample was thoroughly mixed and samples were withdrawn for particle size analysis (performed by the Minerals Engineering Centre, TUNS) and ultimate and proximate analyses (performed by the Nova Scotia Research Foundation Corporation). Particle size measurements were made using a Malvern Instruments (2600 Series) analyzer based on the principle of laser diffraction or ensemble light scattering. A sample coal particle size distribution is shown in Fig. 2.1.

The particle size analyses of all the coals are shown in Table 2.1. The arithmetic volume or mass mean diameter, D_w, is the last entry in each row of Table 2.1. Proximate analyses of the coals are given in Table 2.2; the bold-faced entries are the averages of the three analyses done for each of the four dust samples.

To prevent excessive loss of volatiles and surface oxidation, the coal dust was kept in an inert atmosphere over the duration of testing. This involved first placing the dust in glass mason jars, the tops of which had been fitted with inlet and outlet valves. Each jar was filled with dust to about three-quarters full, and the remaining space was evacuated with a small vacuum pump. The jar was then flushed through with nitrogen to provide the inert atmosphere. The evacuation and purging procedure was repeated for each jar at regular intervals throughout the testing.

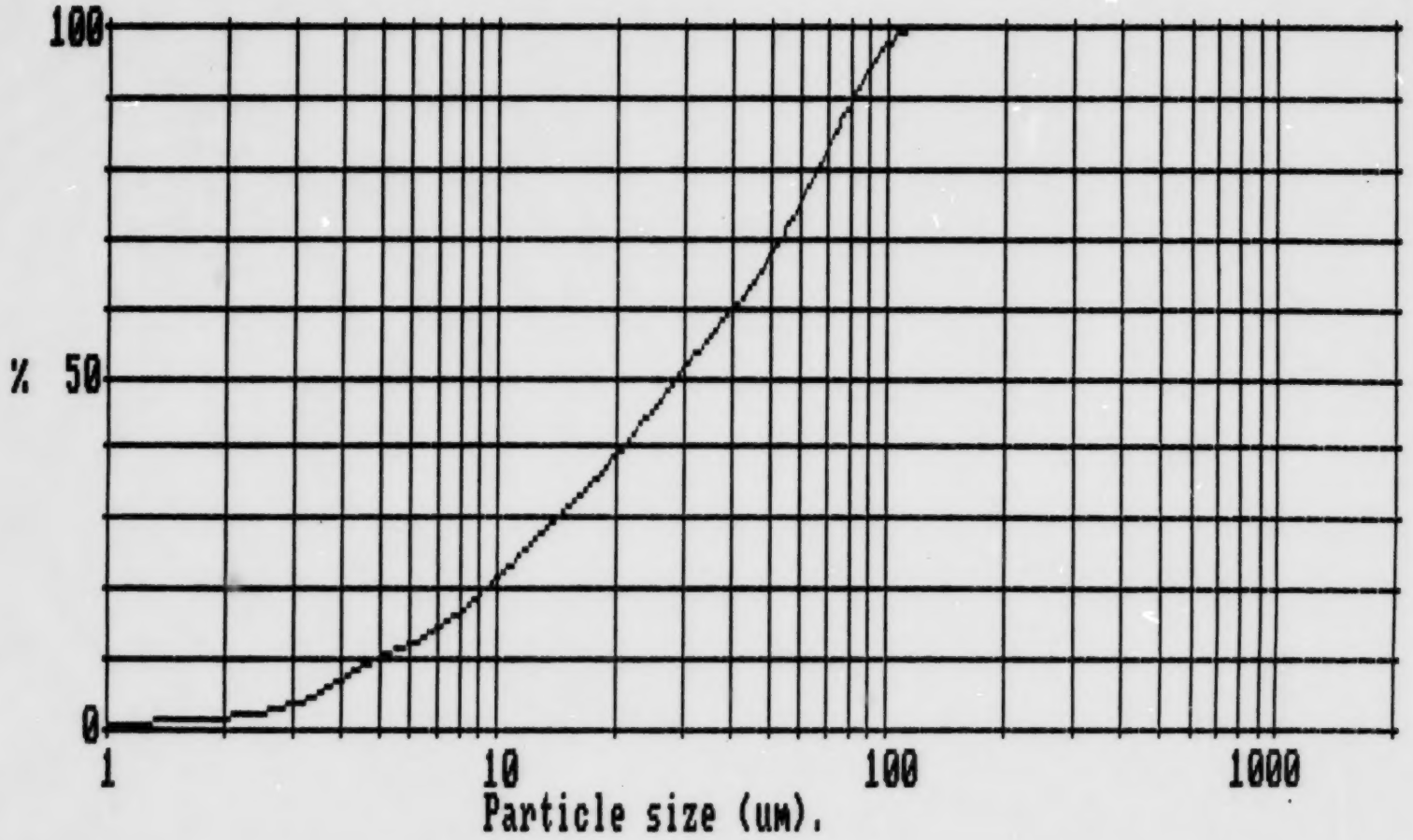


Fig. 2.1 Sample coal particle size distribution (Prince 1) determined by Malvern Instruments (2600 Series) analyzer.

Table 2.1 Particle size analyses of coals.

Coal Dust	< 125 μm [weight %]	<75 μm [weight %]	<45 μm [weight%]	<20 μm [weight%]	D_w [μm]
Prince 1	100	86	64	39	29
Prince 2	100	94	74	47	22
Phalen 1	100	85	61	39	30
Phalen 2	100	99	84	52	19

Table 2.2 Proximate analyses of coals.

Coal Dust	Moisture [%]	Ash [%]	Volatiles [%]	Fixed Carbon [%]
Prince 1	4.4	6.6	37.3	51.7
	4.5	6.6	37.0	51.9
	4.6	6.4	38.3	50.7
	4.5	**6.5**	**37.5**	**51.5**
Prince 2	4.3	7.0	36.3	52.4
	4.3	6.9	36.4	52.4
	4.1	7.0	36.7	52.2
	4.2	**7.0**	**36.5**	**52.3**
Phalen 1	1.7	14.1	30.9	53.3
	1.6	14.3	31.2	52.9
	1.6	13.9	30.8	53.7
	1.6	**14.1**	**31.0**	**53.3**
Phalen 2	1.4	14.1	31.6	52.9
	1.6	14.2	30.3	53.9
	1.6	14.0	30.8	53.6
	1.5	**14.1**	**30.9**	**53.5**

2.2 Rock Dust

Limestone from the Havelock deposit and dolomite from the Kelly Cove deposit were obtained from CBDC. Magnesite was supplied by Canadian Refractories, located in Grenville, Quebec. The limestone and dolomite (both regular grind and -300 mesh) samples were not processed in any matter after receipt at TUNS. The magnesite was received in -5 mm form and was, therefore, ground and sieved at TUNS to an appropriate size.

Each rock dust sample was analyzed by the Minerals Engineering Centre, TUNS, for particle size and composition (calcium carbonate, magnesium carbonate and moisture). A sample rock dust particle size distribution, as determined by the same Malvern analyzer used for the coal dust, is shown in Fig. 2.2. The particle size analyses of all the rock dusts are shown in Table 2.3. Compositional analyses are given in Table 2.4.

2.3 Experimental Program

The experimental program involved two distinct phases of work. The first phase addressed objectives (1) and (2) in section 1.1 and dealt with coal dust/air and methane/coal dust/air ignitability tests according to the scheme outlined in Table 2.5. For each coal type, particle size, methane concentration and ignition energy, tests were conducted at different coal dust concentrations to establish the lean flammability limit (LFL). Coal dust concentrations higher than 1.0 kg/m^3 were not tested. The Prince 2 sample was the most extensively tested coal, in terms of varying the stored ignition energy.

In the second phase of the work, which addressed objective (3) in section 1.1, experiments were carried out on coal dust/rock dust/air mixtures. For each of the four rock dusts listed in Table 2.3, tests were conducted at a fixed coal type and particle size (Prince 2), coal dust concentration (0.5 kg/m^3), methane concentration (0%), and ignition energy (5 kJ). Rock dust concentrations ranged from 20% of the total solids mixture to the percentage required to suppress an explosion.

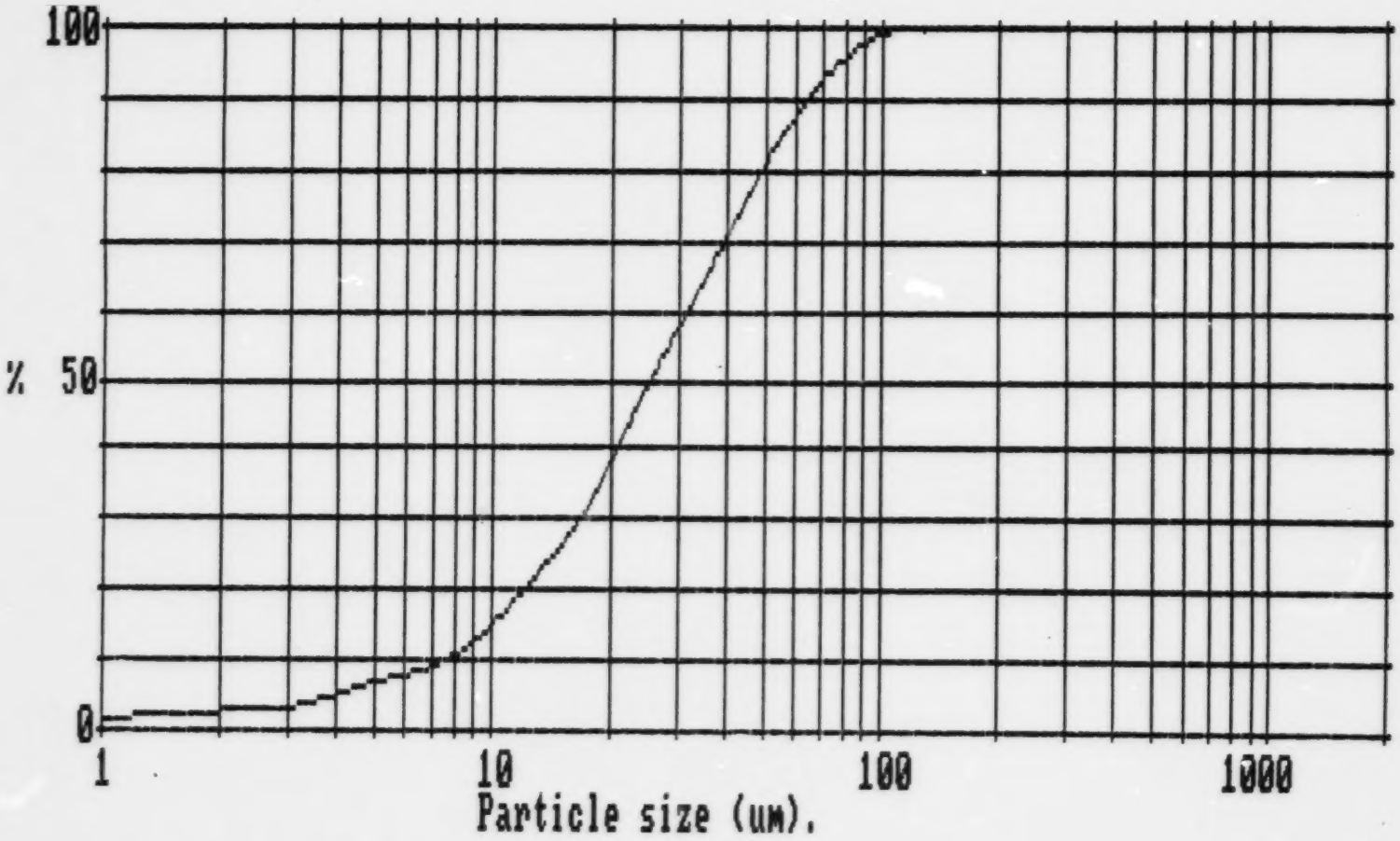


Fig. 2.2 Sample rock dust particle size distribution (limestone) determined by Malvern Instruments (2600 Series) analyzer.

Table 2.3 Particle size analyses of rock dusts.

Rock Dust	< 125 μm [weight %]	<75 μm [weight %]	<45 μm [weight %]	<20 μm [weight %]	D_w [μm]
Limestone	100	95	76	38	25
Dolomite (regular grind)	100	86	63	39	30
Dolomite(-300 mesh)	100	100	88	54	18
Magnesite	100	85	63	41	28

Table 2.4 Compositional analyses of rock dusts.

Rock Dust	$CaCO_3$ [weight %]	$MgCO_3$ [weight %]	H_2O [weight %]
Limestone	98.0	--	0.07
Dolomite (regular grind)	56.0	40.7	0.09
Dolomite (-300 mesh)	56.7	39.2	0.13
Magnesite	14.3	81.3	0.02

Table 2.5 Test matrix for coal dust/air and methane/coal dust/air ignitability experiments.

Coal Type and Size	Methane Concentration [%]	Coal Dust Concentration [kg/m^3]	Stored Ignition Energy [J]
Prince 1	0, 2	> LFL to < LFL	10,000, 5000, 1000, 250, 138, 50
Prince 2	0, 2	> LFL to < LFL	20,000, 15,000, 10,000, 7500, 6000, 5000, 3500, 2500, 2000, 1000, 250, 138, 50
Phalen 1	0, 2	> LFL to < LFL	10,000, 5000, 1000, 250, 138
Phalen 2	0, 2	> LFL to < LFL	10,000, 5000, 1000, 250, 138

Note: Stored ignition energies listed for Prince 2 are for coal dust alone (i.e., 0% methane). Ignition energies used with Prince 2 and 2% methane are the same as those shown for Prince 1.

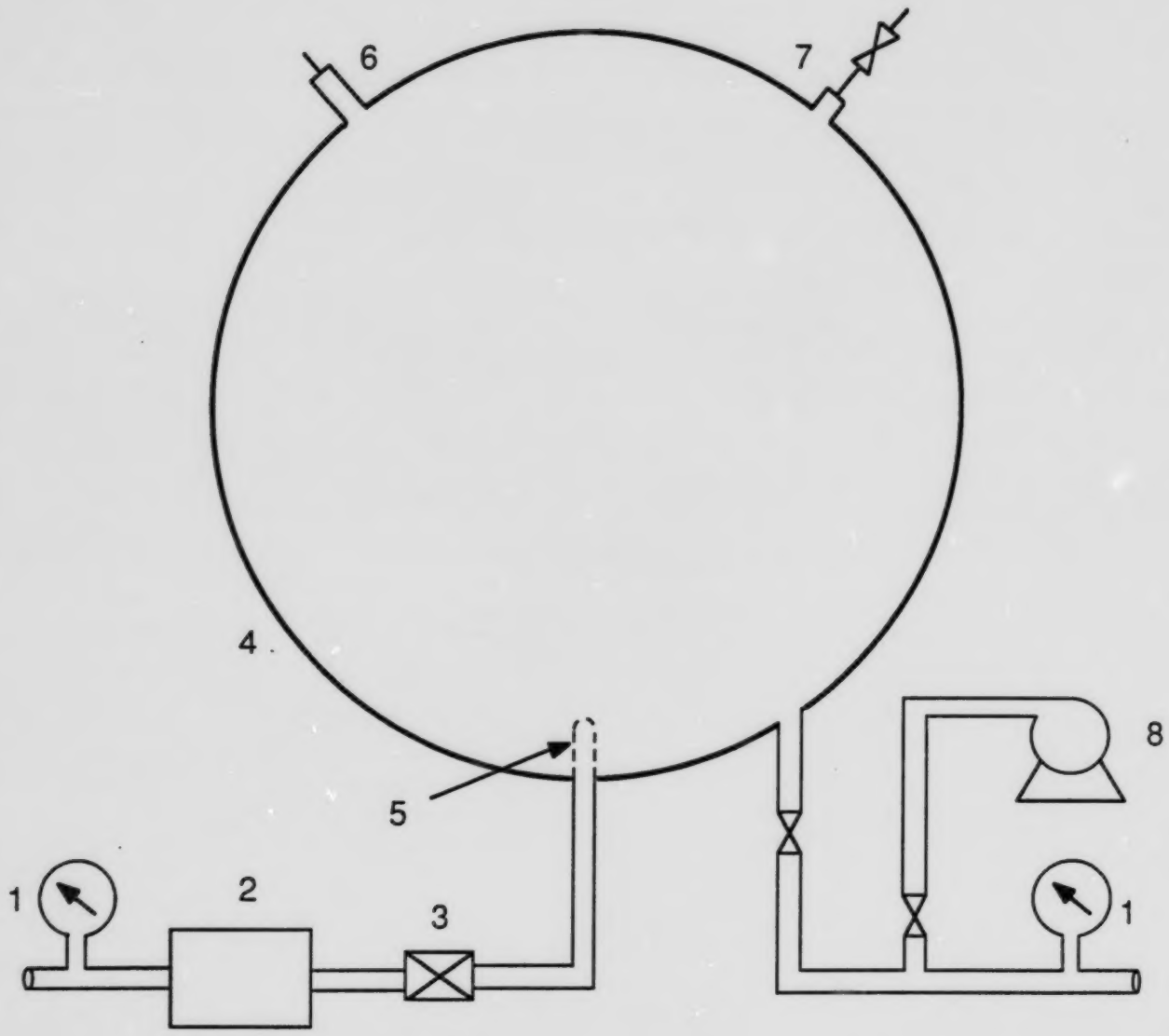
2.4 Apparatus and Procedure

The explosion tests were conducted in a stainless steel, spherical vessel having a volume of 26 L (Fig. 2.3). Prior to each run, the required mass of coal dust was placed in a curved tube located beneath a nozzle housed in the chamber bottom. Dust dispersion through the nozzle was achieved by an air blast from a 1-L reservoir pressurized to 13.8 bar (g). Also before each run, the explosion vessel was evacuated to 0.53 bar so that the dispersion pulse raised the vessel pressure to 1 bar at the time of ignition. Ignition was by either a chemical ignitor or an electric match, centrally mounted in the chamber. A fixed time delay of 400 ms between commencement and ending of dust dispersion, followed by a 10-ms delay before ignition (i.e., a total ignition delay time of 410 ms), was used in all tests.

Pressure development during an explosion was measured by a piezoelectric transducer mounted in the vessel wall. An IBM PC was used to record the pressure-time data for each run. These data yielded values of the maximum explosion pressure, P_{max}, and the maximum rate of pressure rise, $(dP/dt)_{max}$, which enabled the occurrence of the lean flammability limit to be evaluated. The PC was also used to control the dust dispersion and ignition sequence by opening and closing the solenoid valve shown in Fig. 2.3 and firing the chemical ignitor or electric match at the appropriate times.

2.4.1 Methane tests

For tests involving methane, the procedure described above was modified slightly. Methane/air mixtures with the same concentration of methane were made up by the partial pressure method in both the dispersion reservoir and the explosion vessel prior to dust dispersion. The vessel pressure at the time of ignition was still 1 bar, but now the combustion atmosphere contained 2% methane by volume.



1	Pressure gauge	5	Dispersion nozzle
2	Dispersion reservoir	6	Pressure transducer
3	Solenoid valve	7	Exhaust
4	Explosion chamber	8	Vacuum pump

Fig. 2.3 Schematic diagram of 26-L explosion vessel and auxiliary equipment.

2.4.2 Inerting tests

For tests involving rock dust, the experimental procedure was again slightly modified. For the apparatus and test conditions used in this study, approximately 30 g of dust is the maximum amount which can be dispersed through the nozzle and into the chamber. However, for a fixed coal dust concentration of 0.5 kg/m^3 (13 g in 26 L) and rock dust percentages greater than 60%, the total amount of solids (coal dust and rock dust) to be dispersed can be significantly greater than 30 g. Figure 2.4 gives a plot of the mass of rock dust required for various rock dust percentages. It was necessary, therefore, to adopt the procedure recommended by Cashdollar and Hertzberg (1985). Only that amount of dust which could easily be dispersed through the nozzle was placed in the curved-tube reservoir. The remainder was placed on top of the nozzle and was dispersed by the dust/air mixture flowing through the nozzle perforations.

2.4.3 Chemical ignitors

All ignition energies (except 138 J) listed in Table 2.5 were obtained with chemical ignitors of the following energy contents: 10,000 J, 5000 J, 2500 J, 1000 J and 250 J. The ignitors were used singly or in pairs to achieve the desired ignition energy; for example, a 1000-J and a 2500-J ignitor were connected together to yield 3500 J. An ignition energy of 50 J was obtained by modifying a 250-J ignitor (i.e., by removing four-fifths of the explosive powder, which is described in the next paragraph).

The chemical ignitors, manufactured by Fr. Sobbe G.m.b.H. in Germany, have been described by Hertzberg et al. (1986a). Briefly, each ignitor consists of a small plastic cup containing a fixed amount of explosive powder and a fuse wire for electrical activation. The powder is composed of 40% by mass zirconium, 30% by mass barium nitrate and 30% by mass barium peroxide. The plastic cup is capped with a thin paper diaphragm through which protrude two wire leads connected to the internal fuse wire. Ignition sources such as these are routinely used in dust explosion research (for example, Hertzberg et al., 1986a and Mintz, 1989), and have been used by the present authors in previous studies (Amyotte et al., 1991a and 1991b).

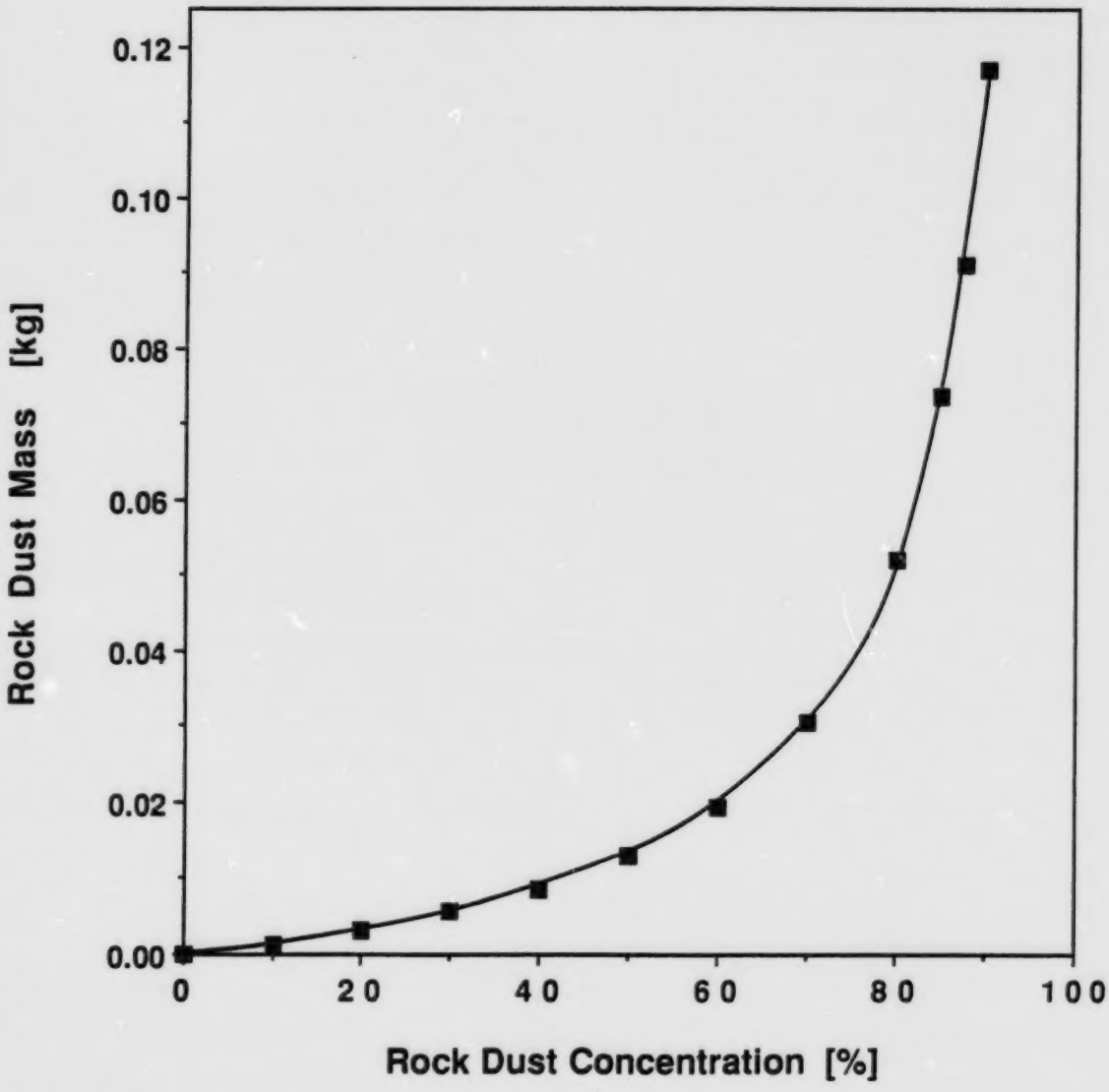


Fig. 2.4 Relationship between mass of rock dust and rock dust percentage.

2.4.4 Electric matches

The 138-J ignition energy was supplied by electric matches (Atlas, type M-103). Each match is composed of a body, bridgewire and head. The body consists of an insulator layer laminated on both sides with solder-coated copper electrodes which are connected by the bridgewire. The match head consists of three pyrotechnic dips and two protective coating dips surrounding the bridgewire. This type of ignitor has been used by other workers in testing the explosibility of dusts (for example, Chippett and Britton, 1985).

2.4.5 Data acquisition and analysis

The IBM PC used to record pressure-time data was interfaced with the piezoelectric transducer through an external analog-to-digital converter. The analog signal from the transducer was sampled at a rate of 5 kHz; this sampling rate has previously been shown to be satisfactory by Swift (1982).

A sample pressure-time trace recorded by the PC is given in Fig. 2.5. The solenoid valve shown in Fig. 2.3 is closed 400 ms after opening; by this time the pressure in the vessel has risen from its initial value of 0.53 bar to about 1 bar. The chemical or electric-match ignitor is fired 10 ms after the solenoid valve closes, and there is a subsequent increase in pressure. The initial shoulder in the pressure trace is due to the ignitor, while the remainder of the trace, including the main peak, is due to the coal dust. The sample trace was recorded for a coal dust concentration well above the lean flammability limit, with ignition by a 5-kJ chemical ignitor.

The maximum explosion pressures given in this report are absolute pressures which have been corrected for the contribution due to the ignitor. In calculating the maximum rate of pressure rise, the procedure recommended by Swift (1982) was followed. The slope at each point was calculated from the slope of a line through three points before and three points after. Thus the slope at each point was a best fit of the data over six time intervals; this derivative calculation procedure was done by the computer software. The solid line in Fig. 2.5, drawn tangent to the steepest

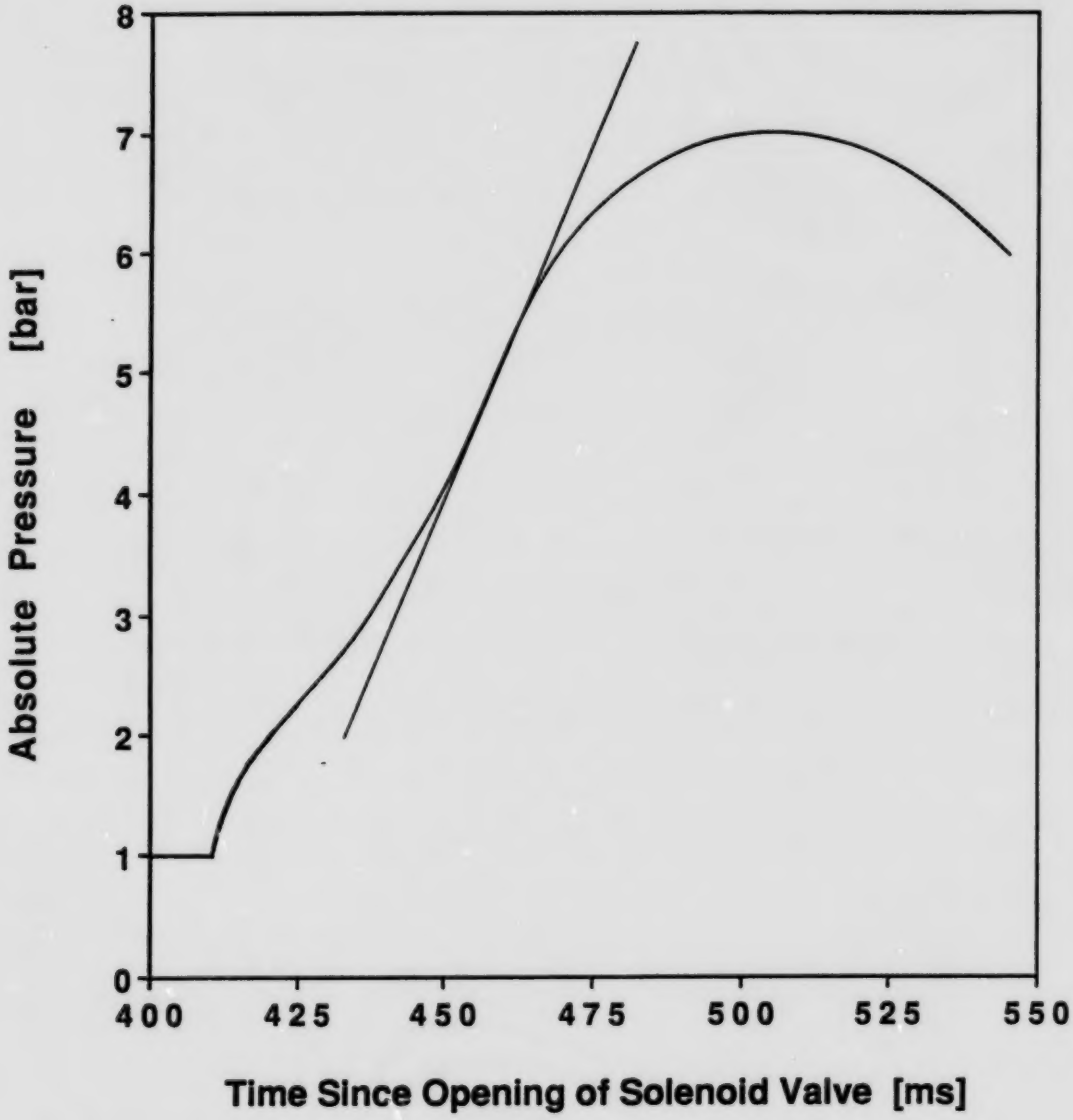


Fig. 2.5 Sample pressure-time trace.

portion of the pressure-time curve, offers a quick visual check on the location where $(dp/dt)_{max}$ occurs.

2.4.6 Spark tests

In addition to the full set of experiments shown in Table 2.5, a limited number of spark-ignition tests were conducted with the Prince 2 coal and 2% methane. For these tests, the computer-based system for dust dispersion and ignition, and data acquisition, was replaced by:

(1) an electrostatic discharge (ESD) tester (Safety Consulting Engineers, model SCEII) to co-ordinate the opening of the dispersing air solenoid valve with the ignition, by electrical spark, of the resulting dust cloud; and

(2) a storage oscilloscope (Tektronix, model T912) to record the pressure development during an explosion.

Also, the 26-L vessel was fitted with electrodes adjusted to a 3-mm gap. All other test conditions (i.e., dispersing air pressure, initial vessel pressure and ignition delay time) were the same as reported in section 2.4.

The ESD tester delivers a high DC voltage across the electrodes to produce a single spark. This is done by first charging a capacitor, or combination of capacitors, to a preset voltage. Five capacitors (5, 10, 20, 50 and 75 μF) are available, and the voltage can be varied from 0 to 450 V DC. Upon initiation of the firing sequence, the solenoid valve opens. After a preset time delay (410 ms in this case), a vacuum relay switch closes to transfer the energy stored in the capacitor(s) to a luminous tube transformer. Here the energy is transformed to a high DC voltage which is delivered to the electrodes. In this study, all capacitors and the maximum voltage of 450 V were used to yield a stored spark energy of 16.2 J, as calculated by the following expression:

$$E = 1/2\, CV^2 \qquad (2.1)$$

where E = energy [J]
C = capacitance [F]
V = voltage [V]

Chapter 3

RESULTS

In this chapter, the results from the explosion tests are presented. Discussion and interpretation of the results are given in the next chapter of the report.

Figures 3.1 to 3.8 present the results of the coal dust/air and methane/coal dust/air experiments. Each plot shows apparent lean flammability limit as a function of stored ignition energy. The word "apparent" is used to indicate that each datum is the measured lean limit at a given ignition energy. The word "stored" is used to indicate that each ignition energy is the maximum which can be theoretically obtained from a given ignitor. The concepts of a "true" lean flammability limit and an "effective" ignition energy are discussed in the next chapter.

Table 3.1 gives the results of the spark-ignition tests conducted for the Prince 2 coal at the 2%-methane level, with a stored spark energy of 16.2 J. The results are shown as a response to the question of whether or not the lean flammability limit was exceeded at a given coal dust concentration.

Figures 3.9 to 3.12 present the results of the coal dust/rock dust/air experiments. Each figure gives two plots; one shows P_{max} (absolute) and the other shows $(dP/dt)_{max}$, both as functions of rock dust concentration.

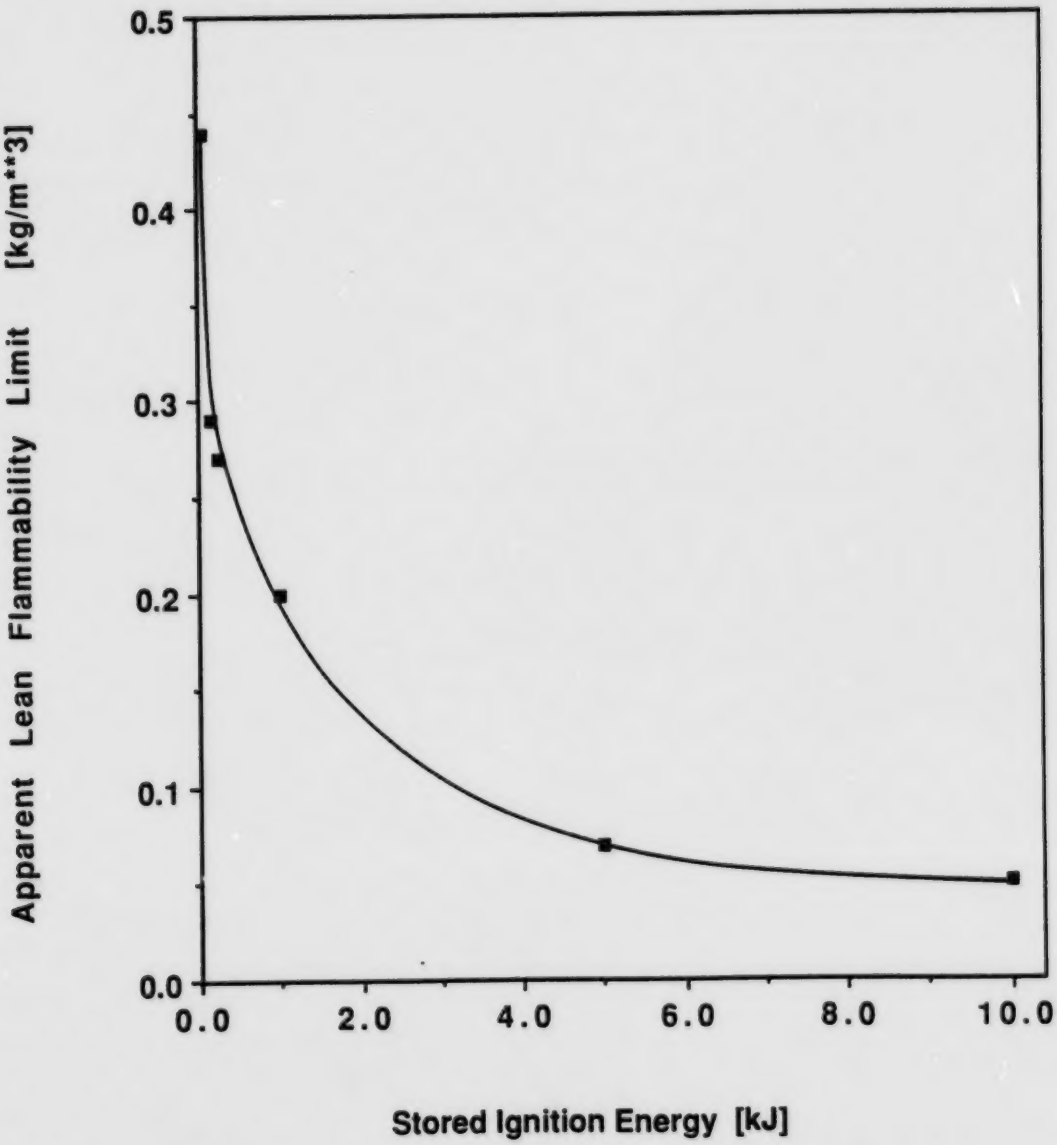


Fig. 3.1 Apparent lean flammability limit as a function of stored ignition energy (Prince 1, 0% methane).

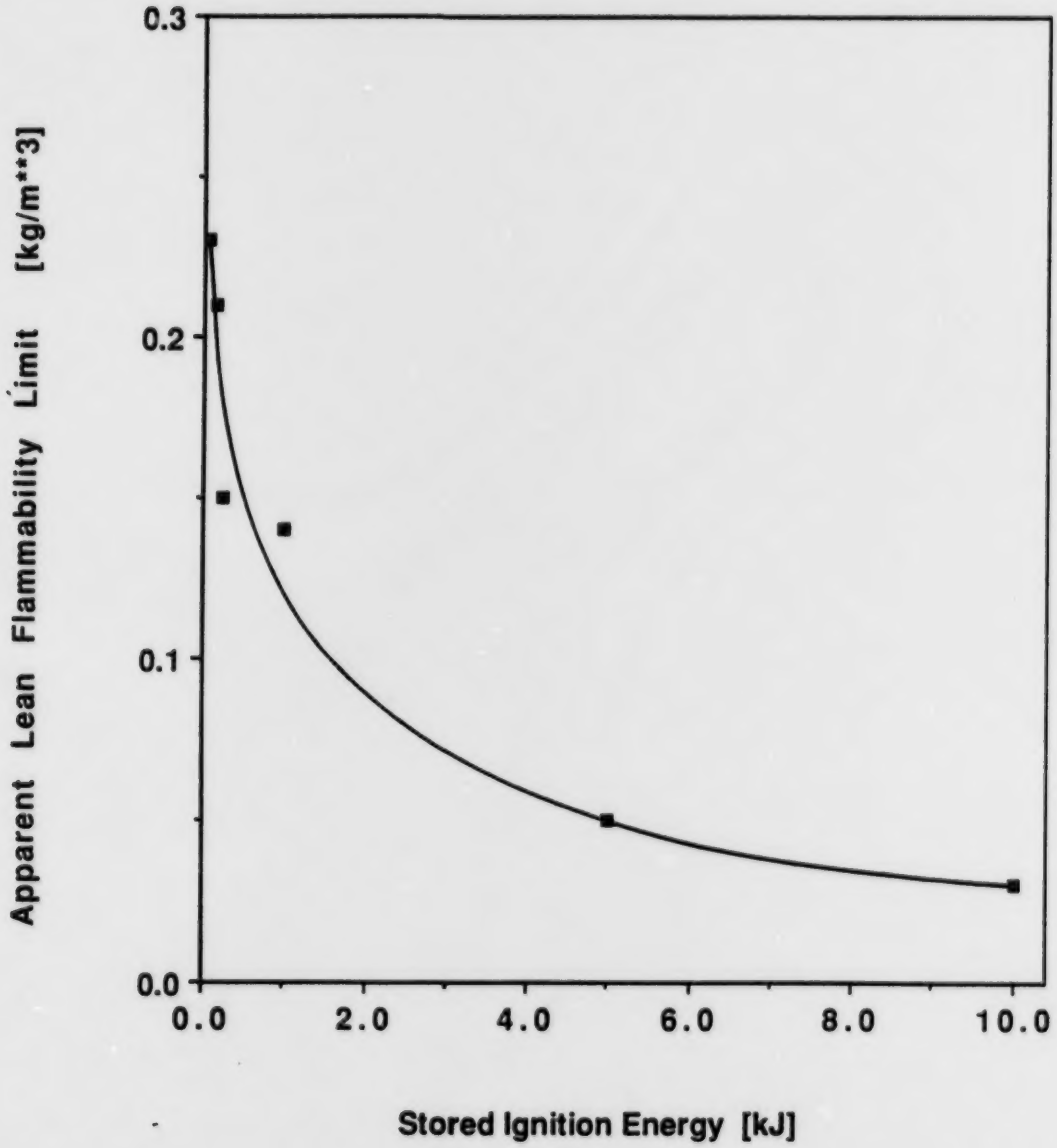


Fig. 3.2 Apparent lean flammability limit as a function of stored ignition energy (Prince 1, 2% methane).

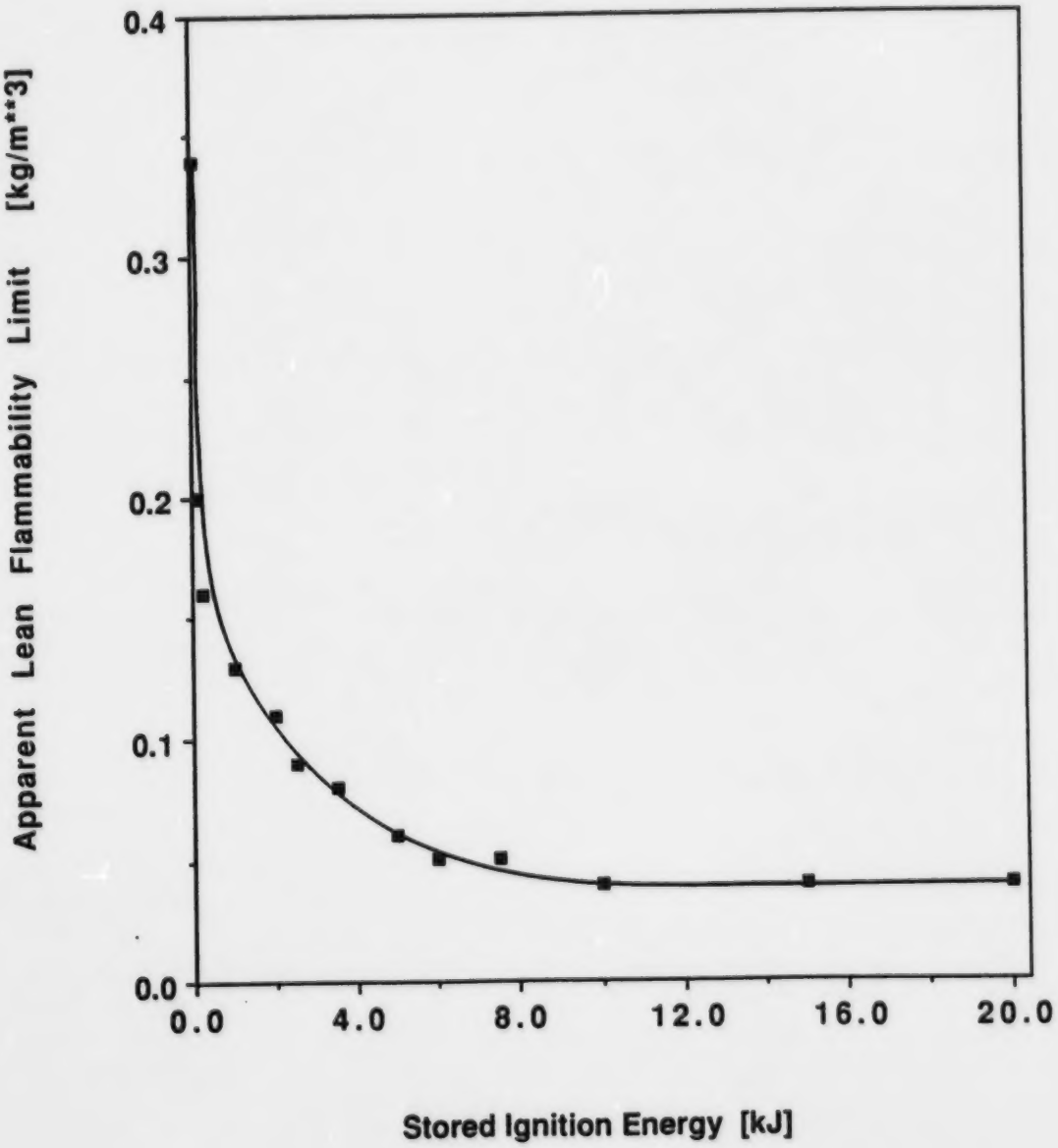


Fig. 3.3 Apparent lean flammability limit as a function of stored ignition energy (Prince 2, 0% methane).

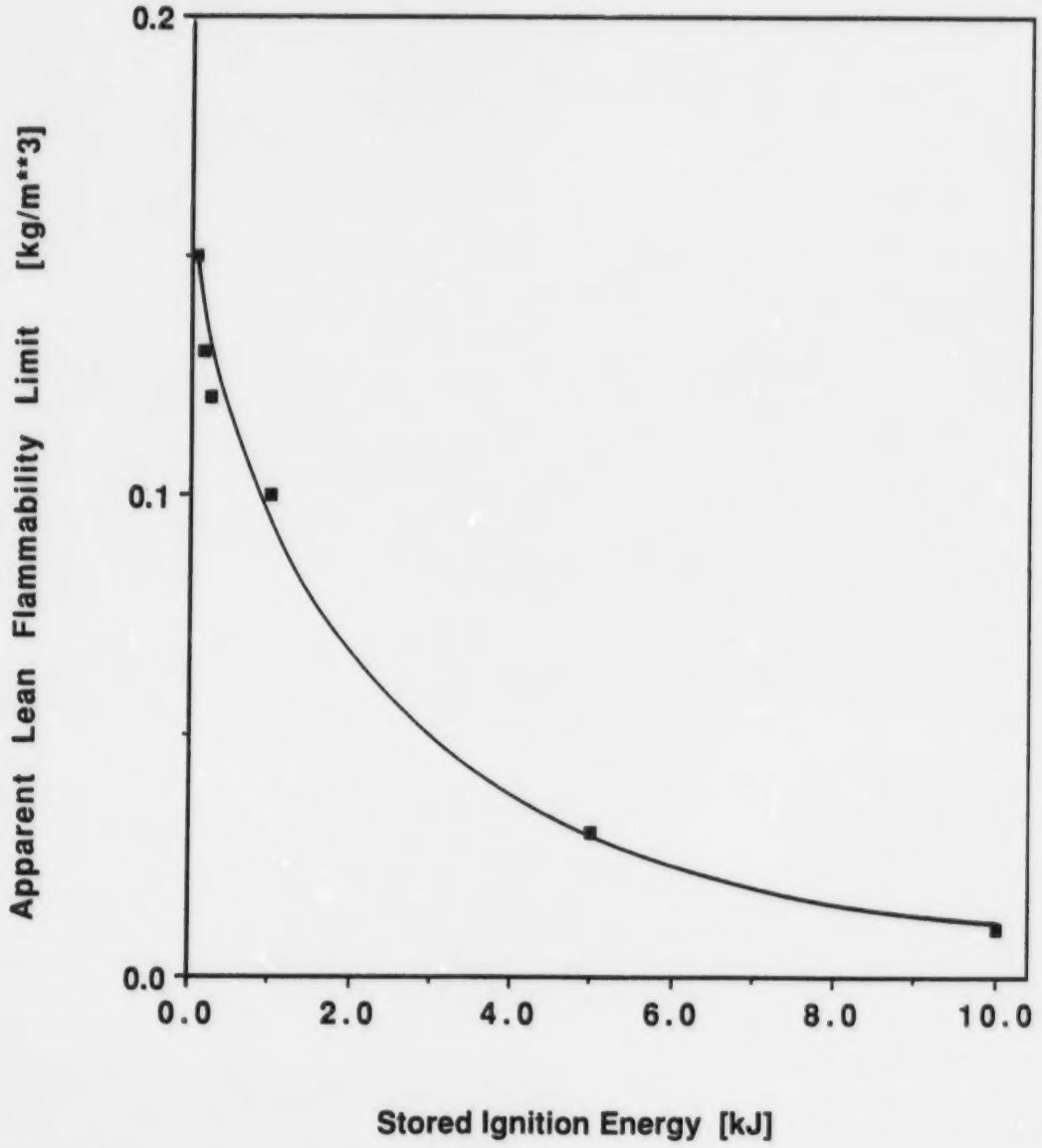


Fig. 3.4 Apparent lean flammability limit as a function of stored ignition energy (Prince 2, 2% methane).

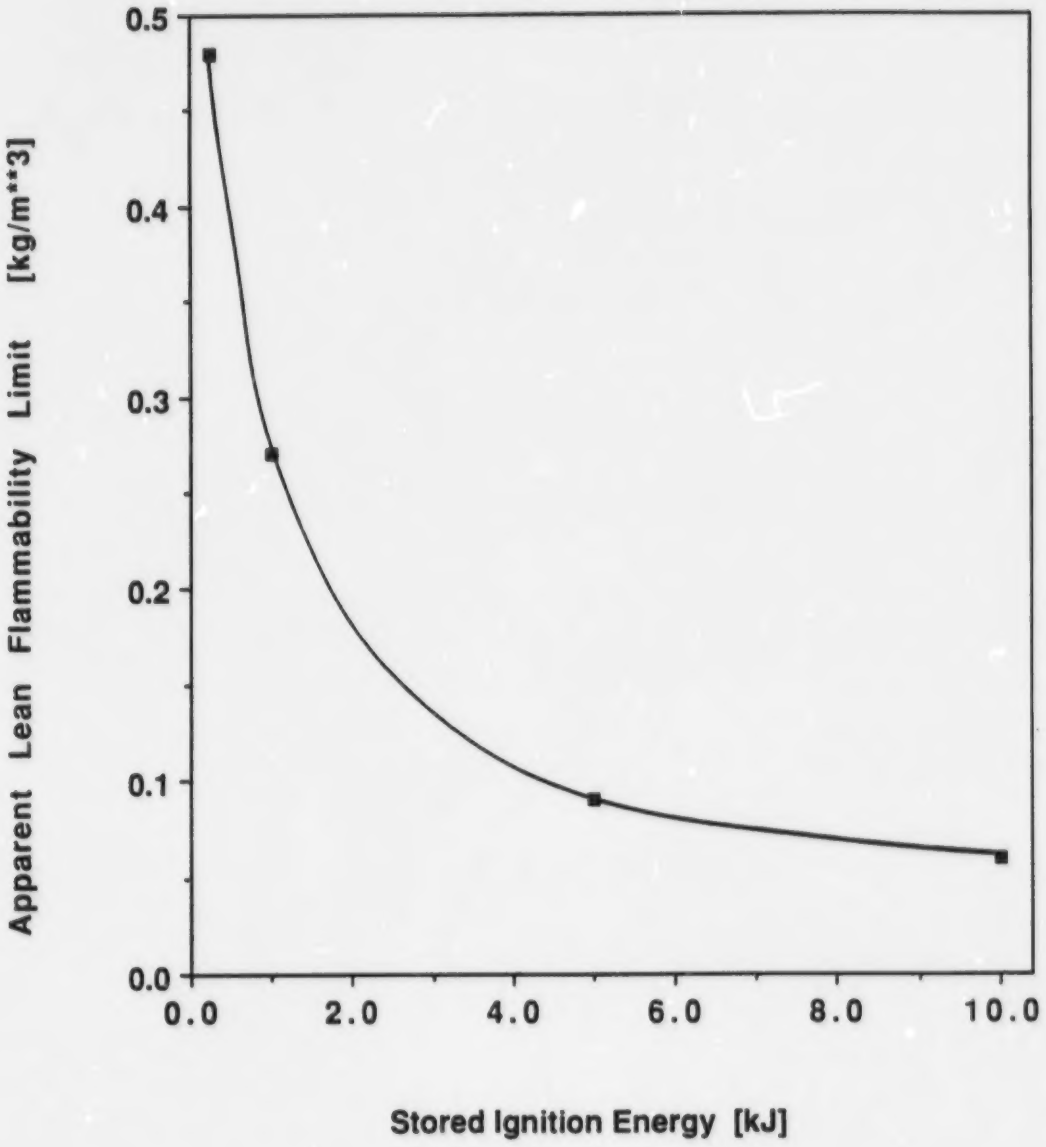


Fig. 3.5 Apparent lean flammability limit as a function of stored ignition energy (Phalen 1, 0% methane).

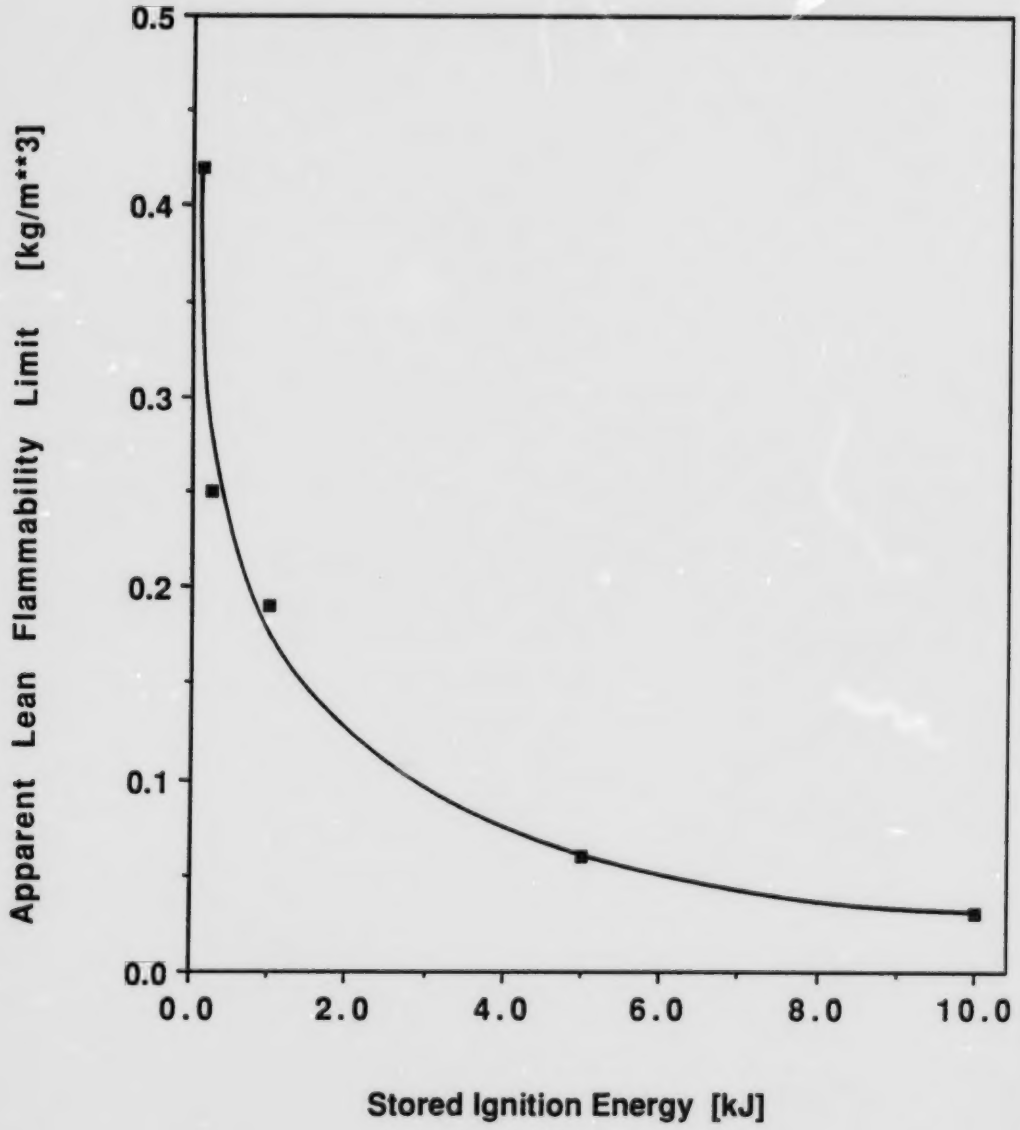


Fig. 3.6 Apparent lean flammability limit as a function of stored ignition energy (Phalen 1, 2% methane).

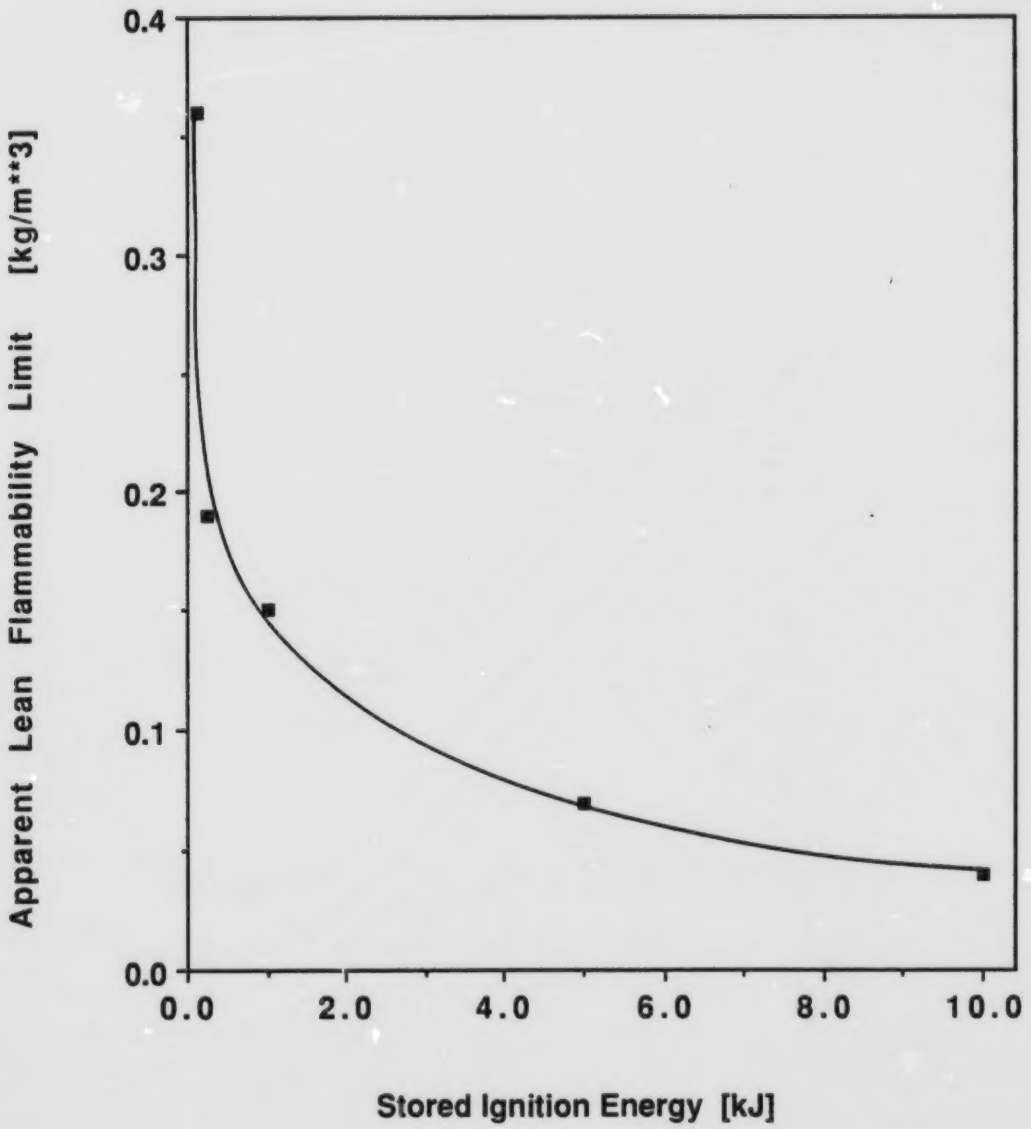


Fig. 3.7 Apparent lean flammability limit as a function of stored ignition energy (Phalen 2, 0% methane).

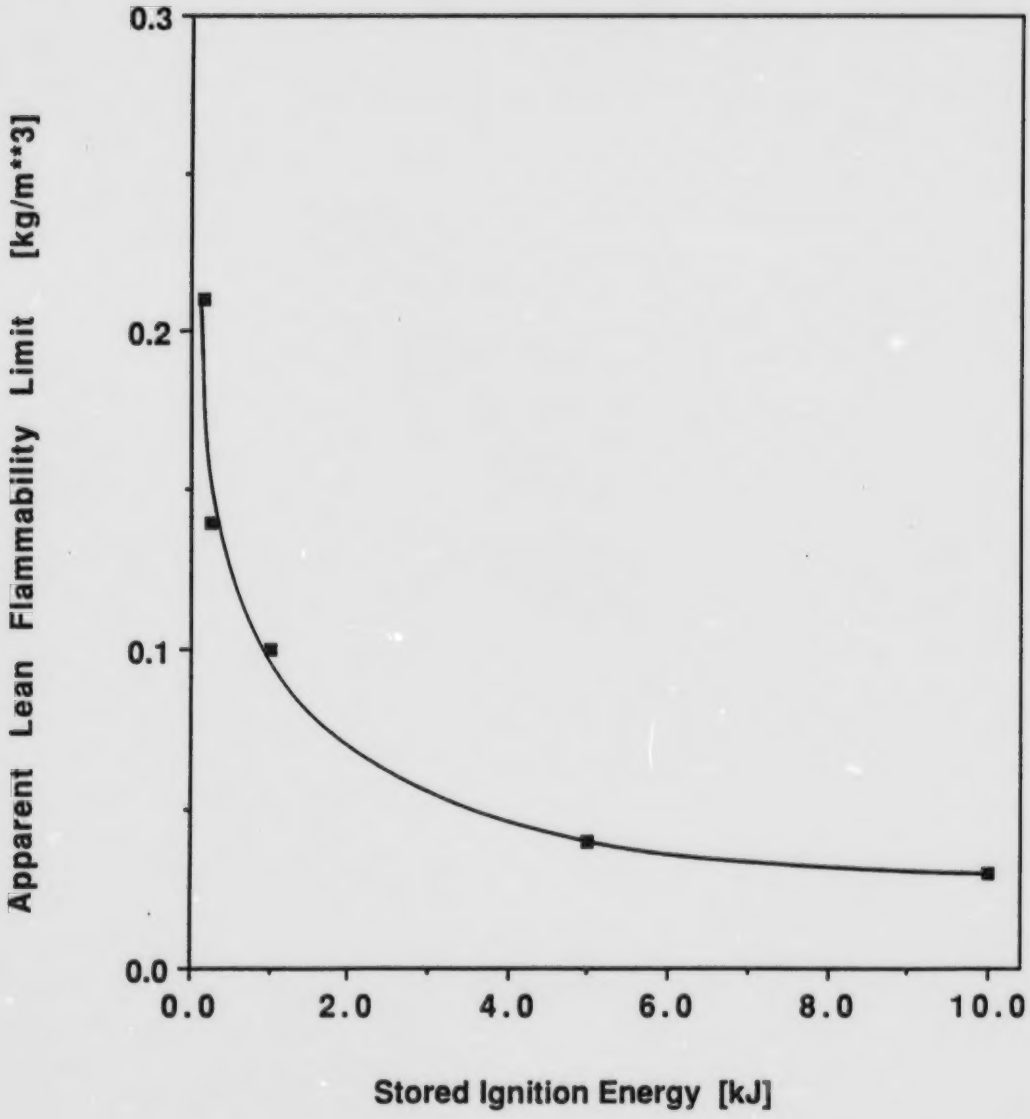


Fig. 3.8 Apparent lean flammability limit as a function of stored ignition energy (Phalen 2, 2% methane).

Table 3.1 Results of tests conducted with stored spark energy of 16.2 J.

Coal Type and Size	Methane Concentration [%]	Coal Dust Concentration [kg/m^3]	LFL Exceeded [?]
Prince 2	2	0.5	No
Prince 2	2	0.7	No
Prince 2	2	0.8	No
Prince 2	2	0.9	Yes
Prince 2	2	0.9	Yes

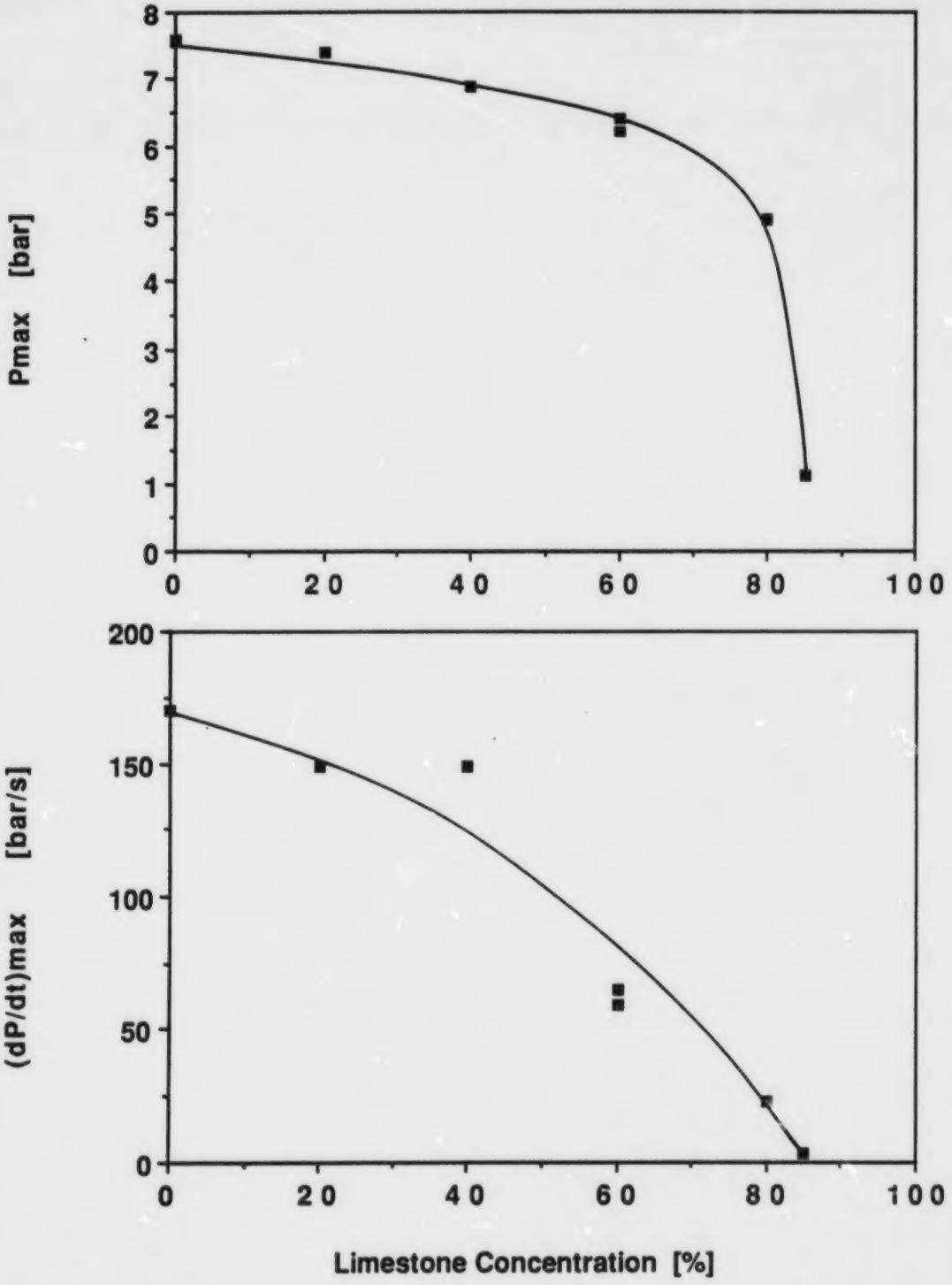


Fig. 3.9 P_{max} and $(dP/dt)_{max}$ as a function of limestone concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).

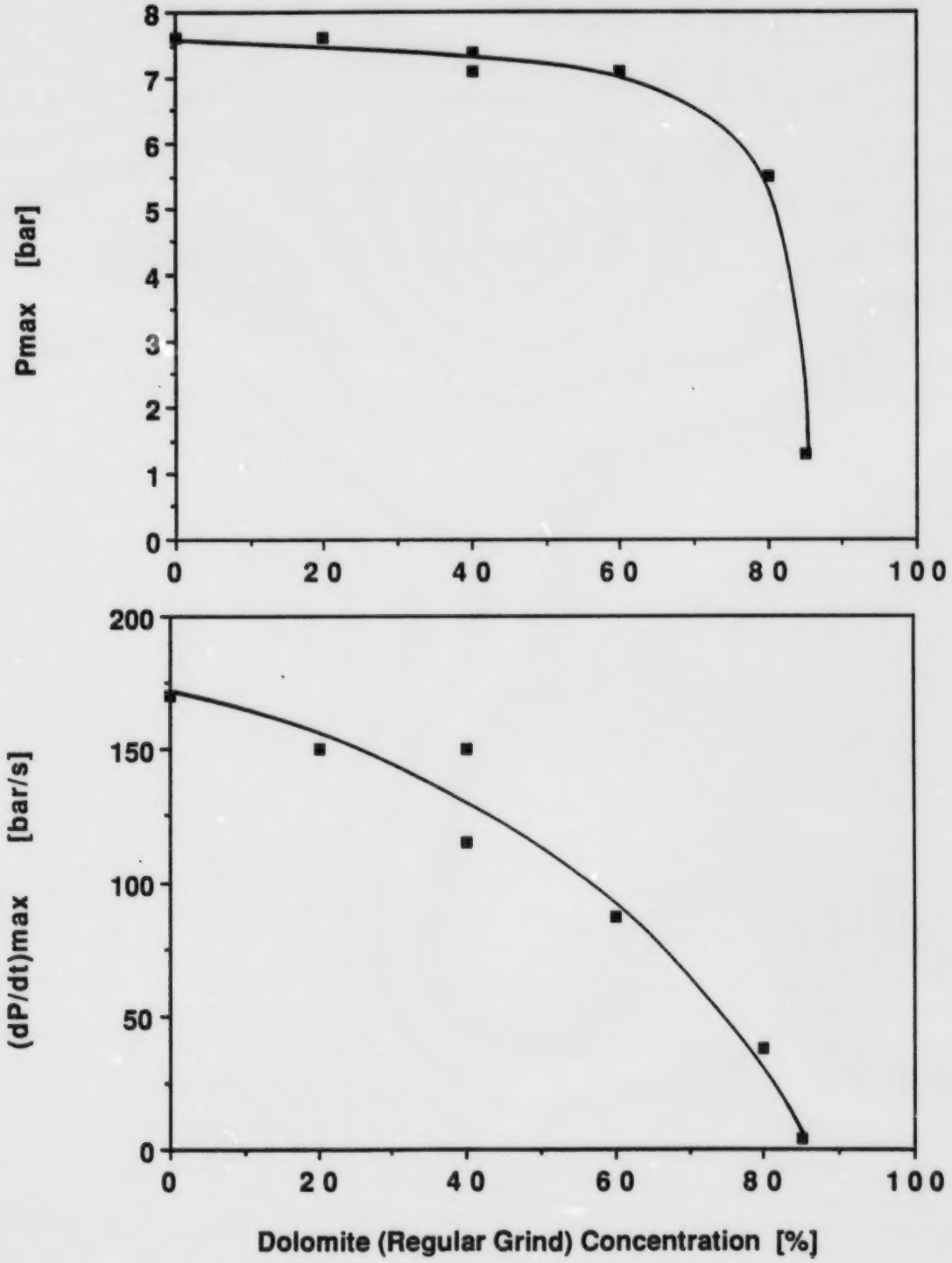


Fig. 3.10 P_{max} and $(dP/dt)_{max}$ as a function of dolomite (regular grind) concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).

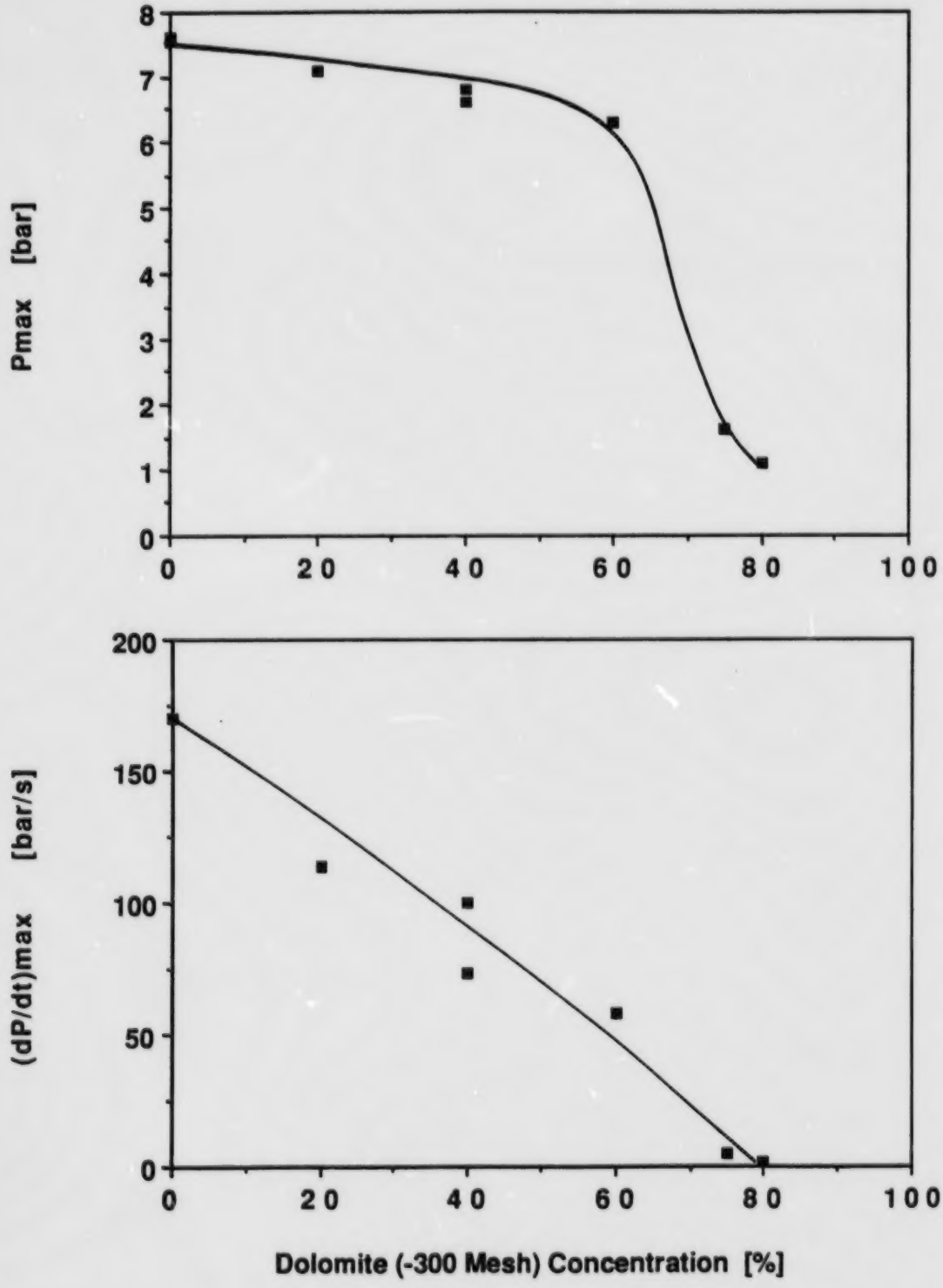


Fig. 3.11 P_{max} and $(dP/dt)_{max}$ as a function of dolomite (-300 mesh) concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).

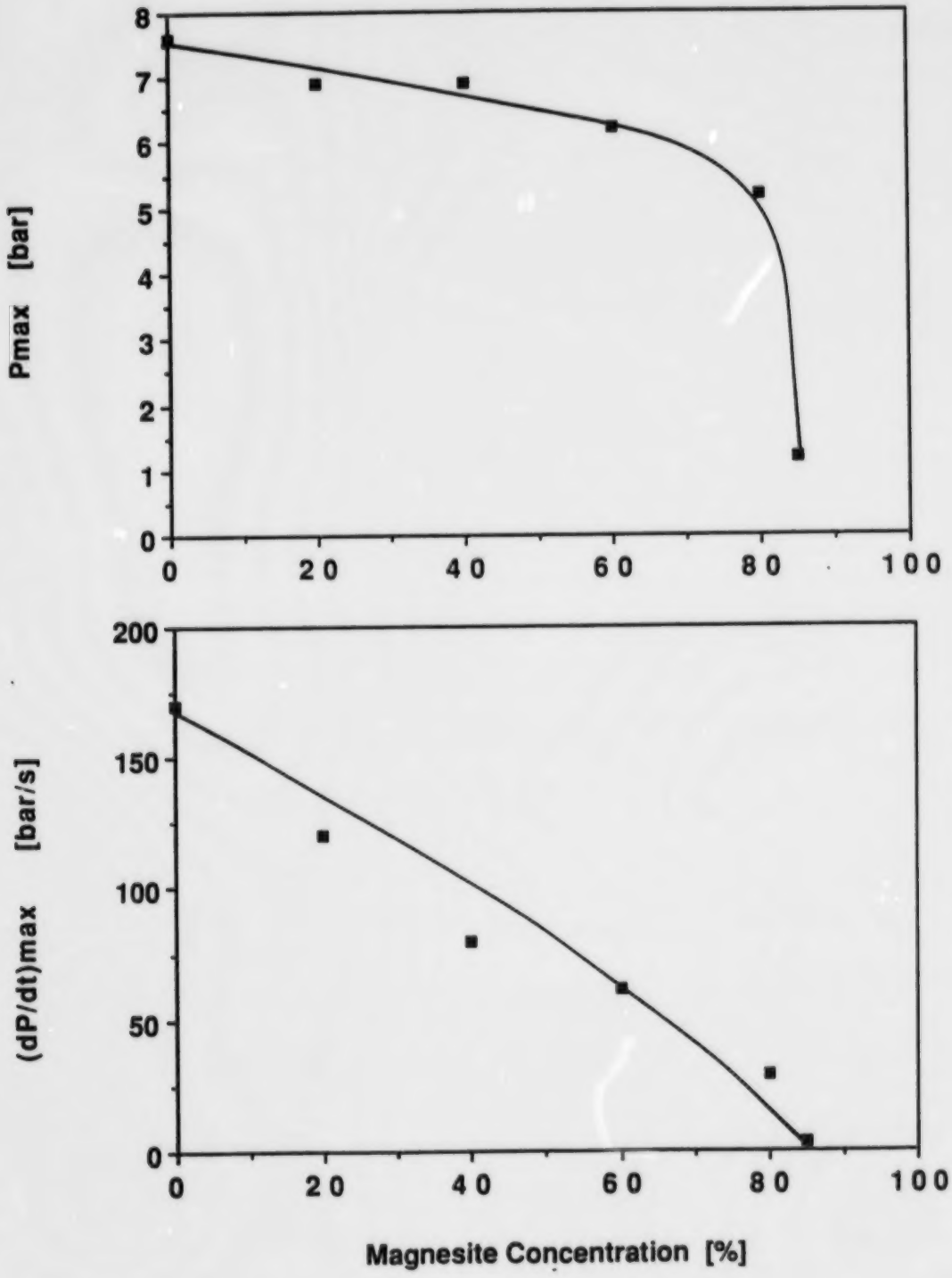


Fig. 3.12 P_{max} and $(dP/dt)_{max}$ as a function of magnesite concentration (Prince 2, 0.5 kg/m^3 coal dust, 0% methane, 5-kJ ignition energy).

Chapter 4
DISCUSSION

The purpose of this chapter is to propose explanations for the results obtained from the experimental work. The results from the ignitability experiments are considered first. This is followed by a discussion of the results from the inerting tests. The final section of this chapter examines the applicability of the results to the coal mining industry.

4.1 Relationship to Previous Work

The current work follows from a previous study carried out by the present authors. Tests were conducted to investigate the explosion behaviour and dolomite inerting requirements of coals from the Prince, Lingan and Phalen mines of CBDC. The coals were examined alone and also with admixed methane, using an ignition energy of 5 kJ in all cases. In the remainder of this chapter, comparisons between current and past work are made where appropriate. Full details on the prior work have been given by Amyotte et al. (1991a and 1991b).

4.2 Lean Flammability Limit: Definition and Criteria

The lean flammability limit is the concentration boundary above which a fuel/oxidant mixture will react explosively in the presence of an adequate ignition source. For dusts, the lean limit (or minimum explosible concentration) is defined as the minimum concentration of dust in a cloud required for sustained flame propagation. Different criteria have been proposed by researchers to quantify the phrase "sustained flame propagation" and hence judge the limit concentration for lean dust/air mixtures. The criteria used here to specify the occurrence of a lean limit were those proposed by Hertzberg et al. (1986a). These are a pressure ratio (P_{max} divided by the initial vessel pressure) greater than or equal to 2 and a value of $(dP/dt)_{max} \cdot V^{1/3}$ greater than or equal to 1.5 bar • m/s, where V is the vessel volume.

In this work the initial vessel pressure was nominally 1 bar, so the pressure ratio is essentially equal to the absolute maximum explosion pressure. As the volume is 0.026 m^3, to

satisfy the requirement of $(dP/dt)_{max} \cdot V^{1/3} \geq 1.5$ bar • m/s, the maximum rate of pressure rise must be at least 5 bar/s in the vessel used in this study. The experimental procedure used was to approach the lean limit from the upper end by decreasing the coal dust concentration in increments of 0.01 kg/m^3. This resulted in a situation where the limit criteria were satisfied at a particular coal dust concentration, but then were not satisfied upon reduction of the dust concentration by 0.01 kg/m^3. The value selected as the lean limit was the last concentration at which the limit criteria were met.

Typical data from this testing procedure are given in Figs. 4.1 and 4.2. As dust concentration is increased, both P_{max} and $(dP/dt)_{max}$ also increase and eventually level off (as shown in Fig. 4.2). These trends are consistent with those observed by Amyotte et al. (1991a) for similar coals.

4.3 Effect of Ignition Energy on Lean Flammability Limit

Figures 3.1 to 3.8 in the previous chapter show the effect of stored ignition energy on the apparent lean flammability limit of each of the coal samples, alone and with 2% admixed methane. In each case the measured lean limit decreases with increasing ignition energy; the decrease is rapid at low energies, with an approach to an asymptotic value of the lean limit at high energies. A curve drawn through the data given in each figure would separate each graph into two regions: a flammable zone to the right of the curve and a nonflammable zone to the left.

The definition of the lean flammability limit given in section 4.2 stated the necessity of having an adequate ignition source. The adequacy of the ignition source can be judged by whether or not the measured lean limit is independent of the ignition energy. This means that the true limit for a particular sample will be the asymptotic value which occurs at high ignition energies. Lean limits less than this asymptotic value are apparent limits because they are dependent on the applied ignition energy. Alternatively, these apparent lean flammability limits can be thought of as ignitability limits because it is really ignitability, rather than flammability, that is being examined at low ignition energies.

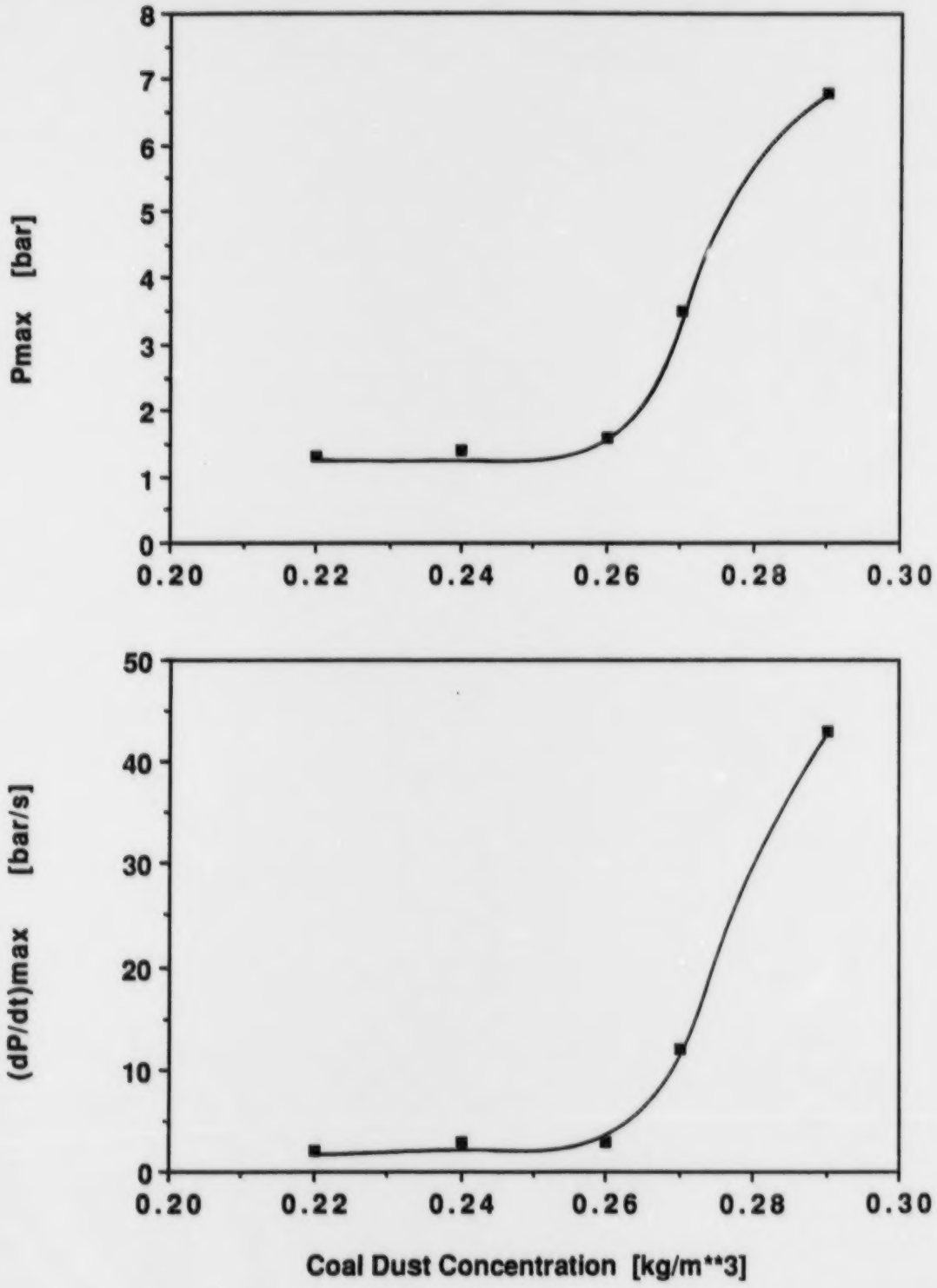


Fig. 4.1 P_{max} and $(dP/dt)_{max}$ at various coal dust concentrations (Phalen 1, 0% methane, 1000-J ignition energy).

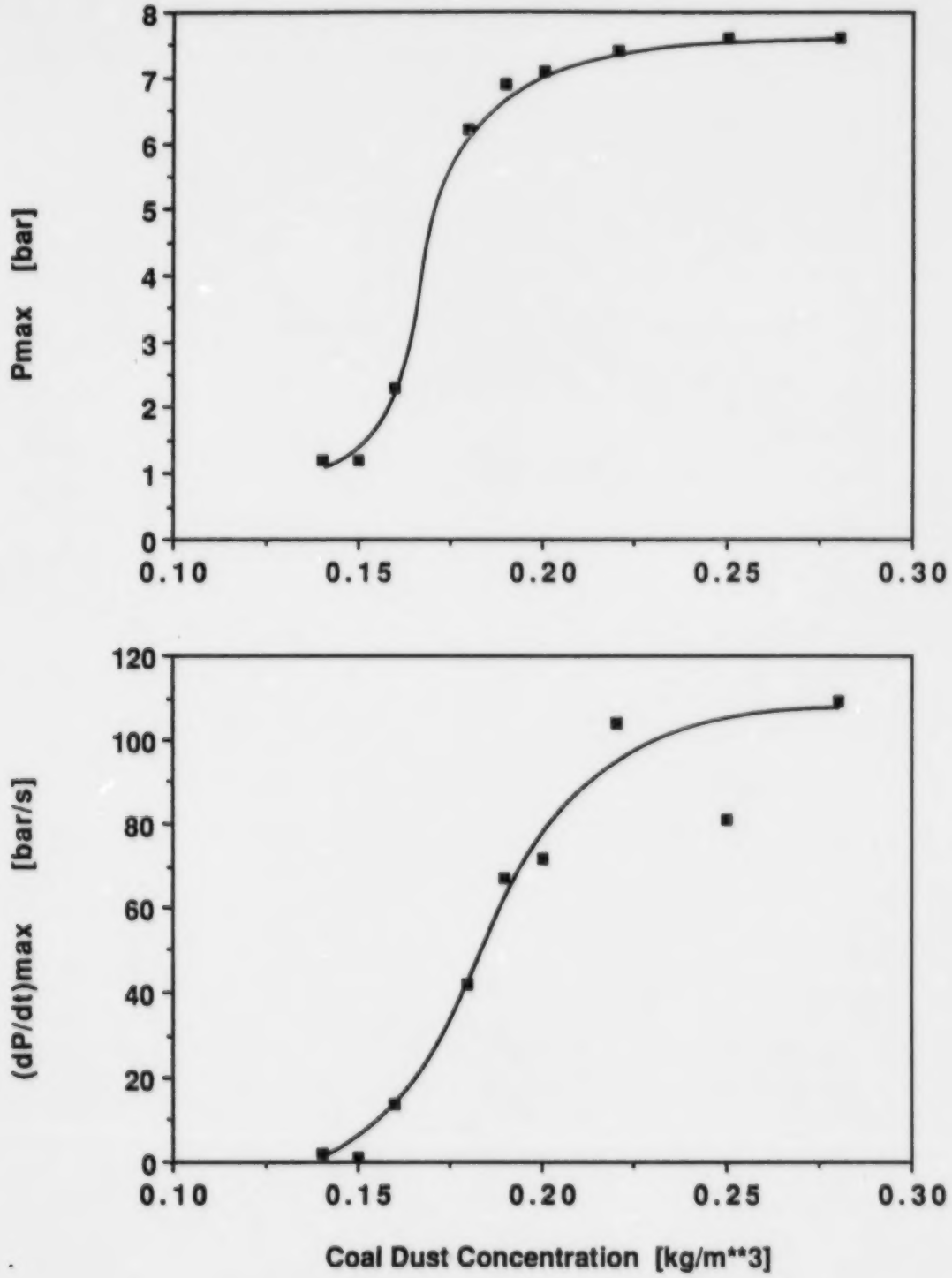


Fig. 4.2 P_{max} and $(dP/dt)_{max}$ at various coal dust concentrations (Prince 2, 0% methane, 250-J ignition energy).

With these points in mind, a re-examination of Figs. 3.1 to 3.8 shows that the true lean flammability limit is not obtained until the stored ignition energy reaches 5 kJ. For energies above this value, there is only a slight lowering of the limit. This is readily apparent for the Prince 2 coal (no methane) which was tested at ignition energies up to 20 kJ (see Fig. 3.3).

Overdriving does not appear to have occurred in Fig. 3.3, although one might question the need for massive ignition energies such as 20 kJ, or even 10 kJ (overdriving is a phenomenon which manifests itself as a downward recurvature after the asymptote has been reached in a plot such as Fig. 3.3). A 10-kJ ignitor is nearly capable of satisfying the lean limit criteria described in section 4.2 by itself, i.e., in the absence of any coal dust or methane. An ignition energy of 5 kJ is judged to be sufficient for measuring true lean limits in the vessel used in this study and with the specified test conditions and limit criteria. This energy provides an asymptotic value of the lean limit, does not overdrive the explosion, and cannot meet the limit criteria on its own. Further justification for accepting 5 kJ as an "adequate" ignition energy is given in the following discussion.

From a practical point of view, it is more important to know whether the lean flammability limit of a dust is 0.48 kg/m^3 (Phalen 1, no methane, 250-J energy) or 0.09 kg/m^3 (5 kJ), than it is to know whether the limit is 0.09 kg/m^3 (5 kJ) or 0.06 kg/m^3 (10 kJ). The necessity of using an adequate ignition energy is further demonstrated by the Phalen 1 data when it is considered that no explosions were recorded for this sample with a 138-J energy at concentrations up to 1.0 kg/m^3. Had this been the only ignition energy tested, the erroneous conclusion that the sample was non-explosive could have been reached. Arguably, this conclusion might be rejected without further testing because of the well-established explosion hazard associated with coal dust. However, the above scenario of an incorrect conclusion concerning the explosive nature of a dust is plausible if the material is one about which little is known.

Before closing this section, there are two further points to note. The first is that the lean limits measured with the 5-kJ ignitors, and reported here, compare favourably with those obtained previously by Amyotte et al. (1991a) for similar coals and the same ignition energy. The second

point is that although the ignitability of dusts played a central role in the current work, this study is not an investigation of minimum ignition energies. Minimum ignition energy may be defined as the quantity of energy which will just ignite a specified concentration of dust. The energy which just ignites the most readily ignitable concentration is referred to as the lowest minimum ignition energy (or simply **the** minimum ignition energy of the dust). Measurement of minimum ignition energies involves experimental considerations beyond the scope of the current work (for example, ensuring that the turbulence level in the dust/air mixture does not adversely affect the combustion process).

4.4 Stored and Effective Energies

The ignition energies shown in Figs. 3.1 to 3.8 are stored energies; they are nominal calorimetric energies which represent the maximum theoretically available from each ignitor. Hertzberg et al. (1986a) have shown that not all of this energy is released when an ignitor is exploded. They recommend the following expression for calculating effective energies:

$$E_{eff} = 5/2\ V\Delta P \qquad (4.1)$$

where E_{eff} = effective energy

V = vessel volume

ΔP = pressure rise due to ignitor alone

The first step in using this equation was to measure the pressure rise caused by each ignitor by itself. A linear relationship between ΔP and stored ignition energy was observed, as shown in Fig. 4.3 (ΔP due to the 50-J ignitor was too low to be accurately measured and is, therefore, not reported in Fig. 4.3). With these values of ΔP, a volume of 26 L, and the appropriate conversion factors, eqn. (4.1) yielded the effective energies given in Fig. 4.4.

The lean limits shown in Figs. 3.1 to 3.8 could be replotted as a function of effective, rather than stored, energy. Because of the linear relationship between effective and stored energies (Fig. 4.4), however, no new information is gained by doing so. It is important to recognize,

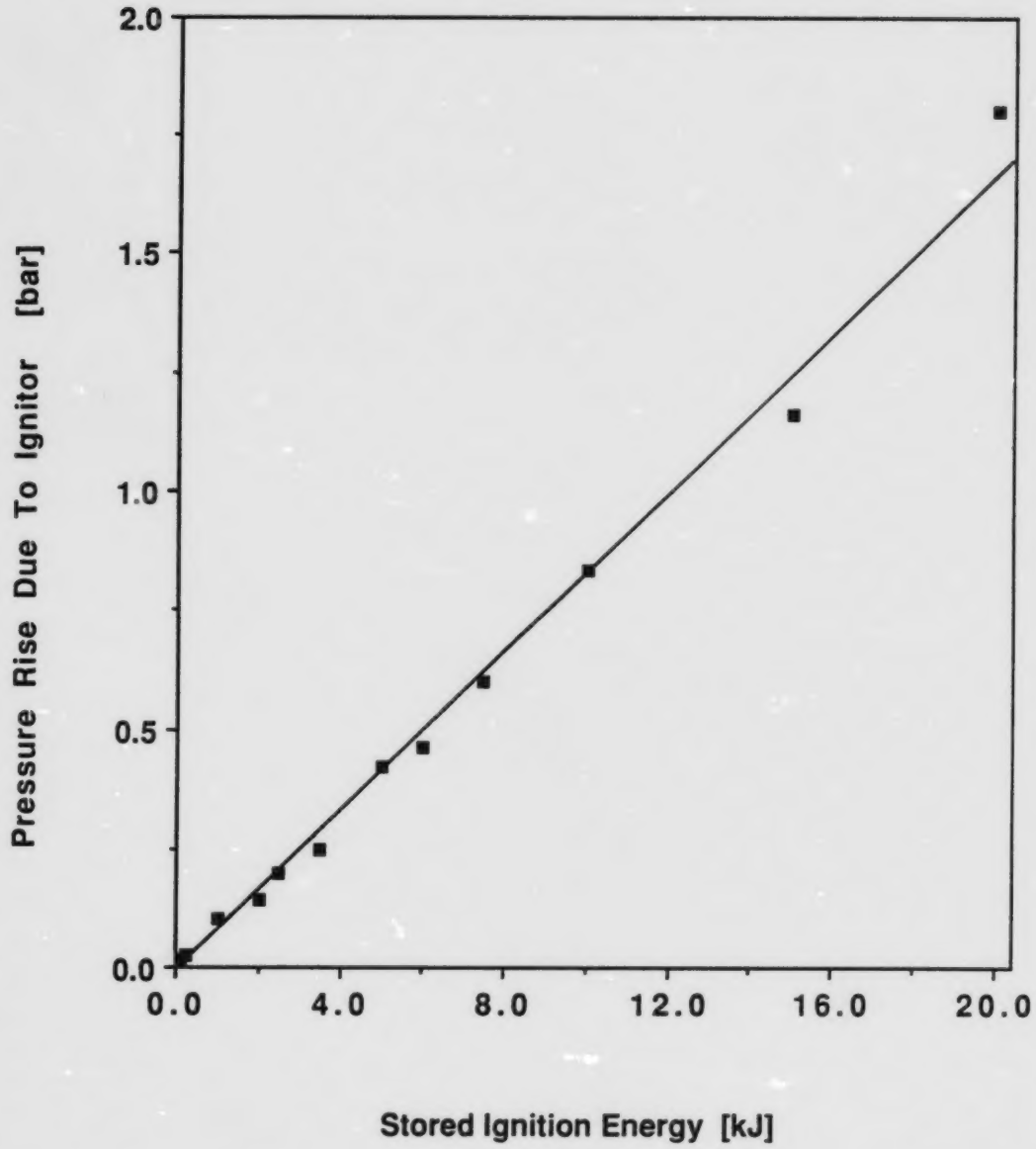


Fig. 4.3 Relationship between pressure rise due to ignitor and stored ignition energy.

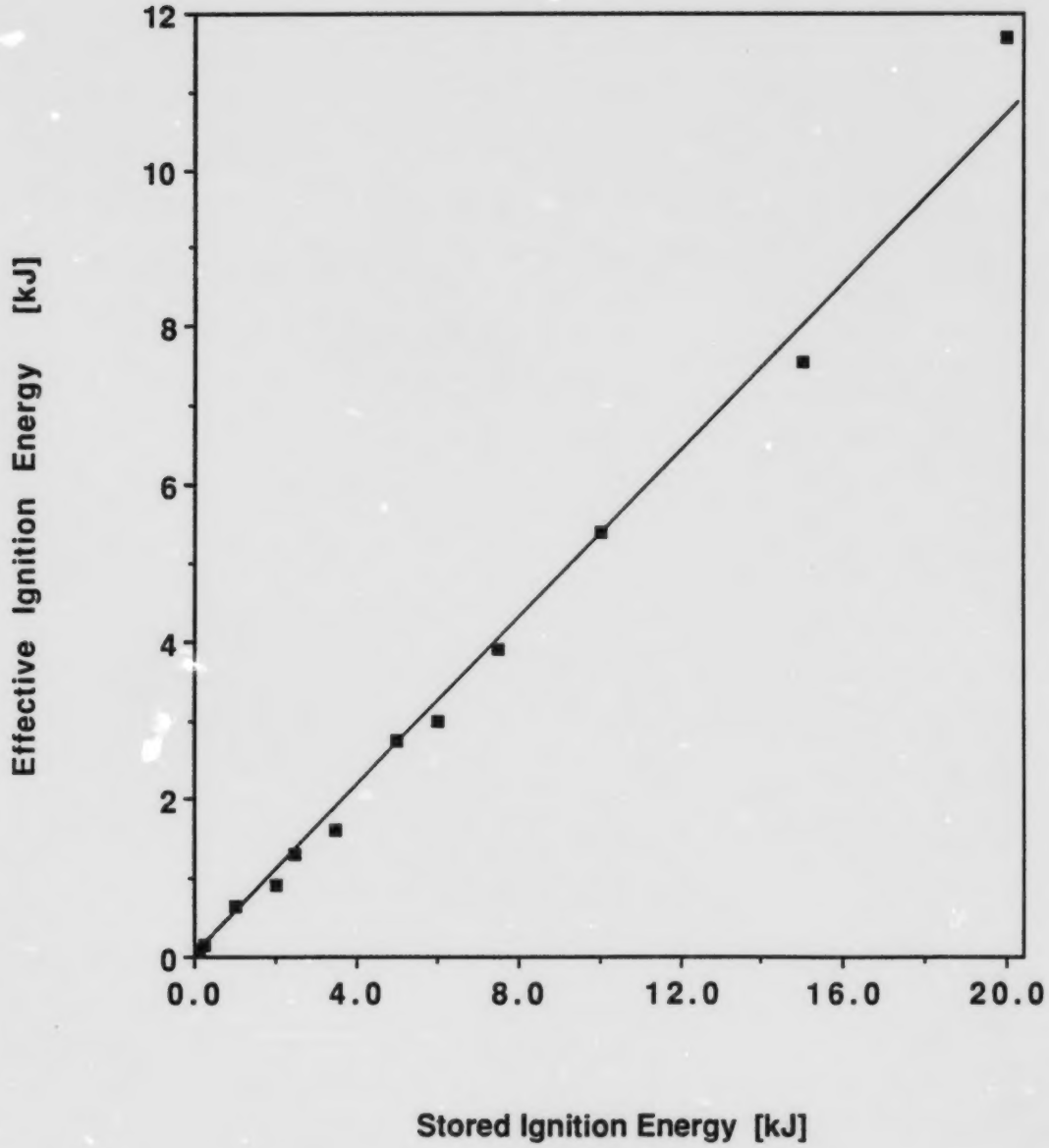


Fig. 4.4 Relationship between effective ignition energy and stored ignition energy.

though, that on average only 55% of the stored energy of the various ignitors was converted to effective energy.

The Prince 2 (no methane) data has been replotted in Fig. 4.5 to demonstrate that the results from this study are consistent with those of other researchers, in particular Hertzberg et al. (1986a). An effective energy of 28 J was calculated for the 50-J stored energy by using the average conversion of 55% from stored to effective energies. Hertzberg et al. (1986a) present data for Pittsburgh seam bituminous coal dust in the manner shown in Fig. 4.5. The trends in their data and those reported here are identical, although the asymptote occurs at higher ignition energies in the current work.

4.5 Spark Tests

As previously mentioned, a limited number of spark-ignition tests were conducted with the Prince 2 coal at the 2%-methane level. The Prince 2 coal was chosen because it was judged to be the most reactive sample, considering both particle size and volatile content. Combined with a 2%-methane oxidizing atmosphere, this was the most promising set of conditions for spark ignition. Even so, the results in Table 3.1 indicate that the apparent lean limit lies between 0.8 and 0.9 kg/m^3, for a stored spark energy of 16.2 J. This stored energy represents an effective energy of approximately 2 J, estimated by using the fact that typical spark generation circuits, such as used here, are only about 10% effective.

After completing these tests, it was felt that further spark ignition experiments would be of rather limited value. Neither this statement, nor the results on which it is based, should be interpreted as meaning that these coal samples are not ignitable by electric sparks. In numerous studies, coal dust clouds have been shown to explode following passage of an electric spark. The main factor limiting the success of spark ignition in this study is the turbulence intensity in the dust cloud at the time of attempted ignition. It can safely be concluded that avoidance of electric sparks

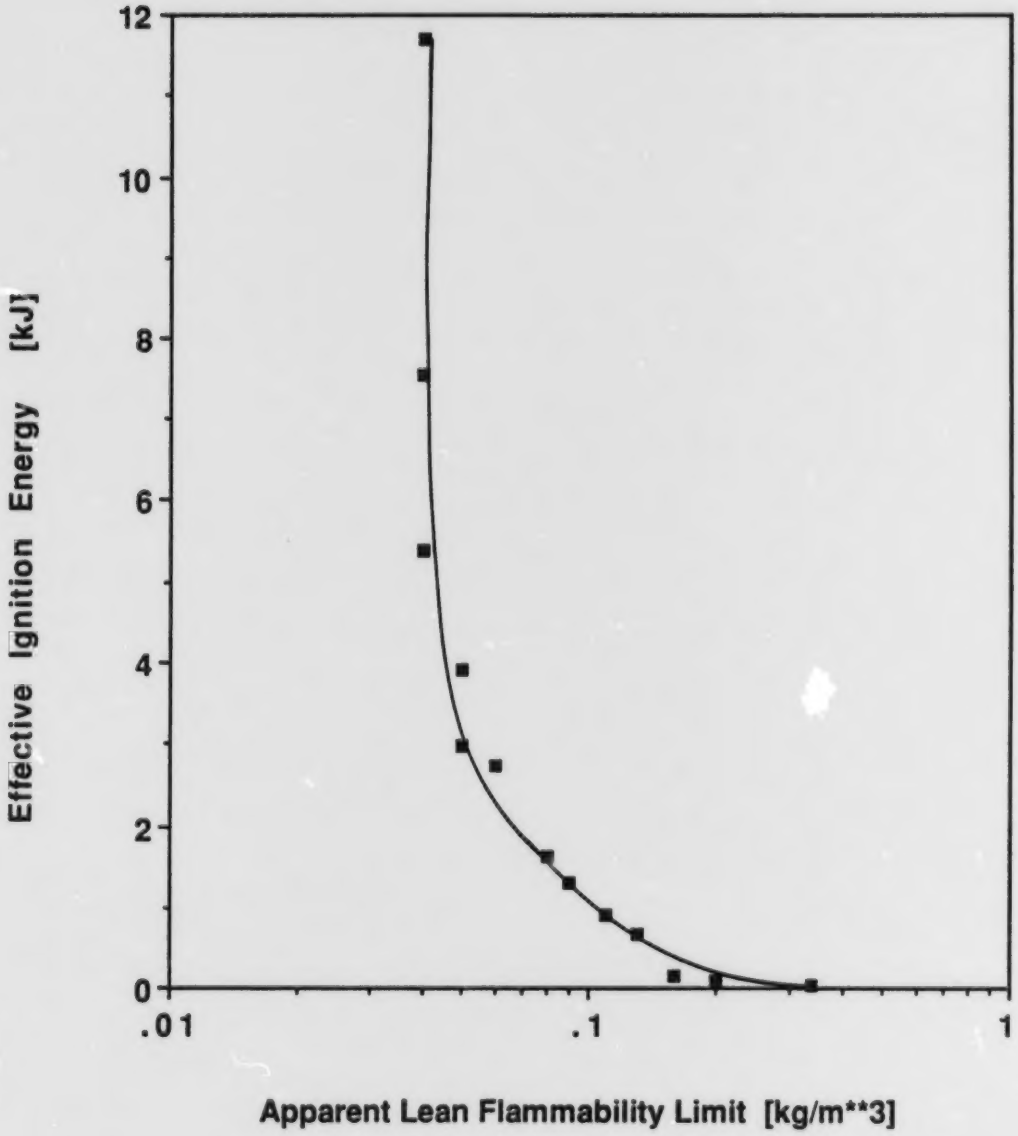


Fig. 4.5 Effect of effective ignition energy on apparent lean flammability limit (Prince 2, 0% methane).

is one of the several requirements for protection from the coal dust explosion hazard. Furthermore, a primary explosion of methane can also be initiated by electric spark (as explained in section 1.3 of the Introduction).

4.6 Ignition Source Geometry

It is known that factors other than ignition energy affect the lean flammability limit: for example, ignition power, power density, and ignition source geometry. While power and power density are somewhat beyond the scope of this work, the ignitor geometry merits some discussion here.

A single electric spark is clearly a point source which acts over an effective distance measured in mm. The electric matches and chemical ignitors, however, are more volumetric in their action. It can be hypothesized that the radius of influence for the matches is measured in cm and that for the chemical ignitors, especially the more energetic ones, in dm. As the ignition source is changed from a low-energy spark to a moderate-energy match to a high-energy chemical ignitor, the ignition volume, as well as energy, is increased. Both factors can lead to a decrease in the measured lean limit.

To further examine this point, the Prince 2 coal (no methane) was tested with 138-J chemical ignitors made up by removing some of the explosive powder from 250-J ignitors. There was, however, no measurable difference in the lean limits as determined by the 138-J chemical ignitor or the 138-J electric match. The conclusion reached is that 138 J is a low enough energy that the powdered chemical ignitor and the fused-solid electric match behave essentially the same with respect to ignition characteristics. It is still expected that the 5-kJ and 10-kJ ignitors involve more of the dust cloud in the ignition process than do their lower energy counterparts.

4.7 Effect of Methane Admixture on Lean Flammability Limit

The effects of adding a small amount of methane (2% by volume) to the oxidizing atmosphere are shown in Figs. 4.6 to 4.9. For each coal sample, the apparent lean flammability

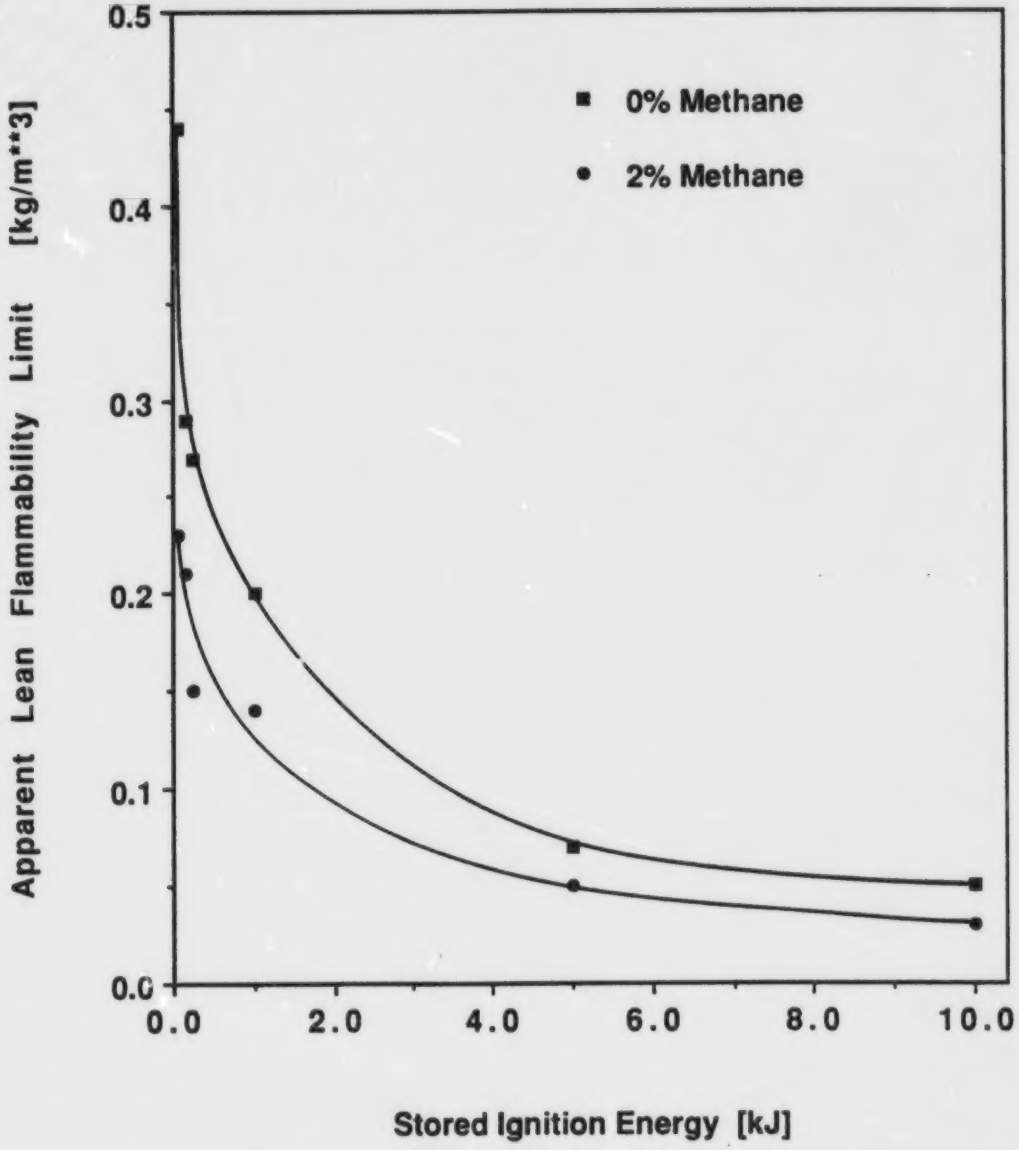


Fig. 4.6 Effect of methane admixture on apparent lean flammability limit of Prince 1 coal.

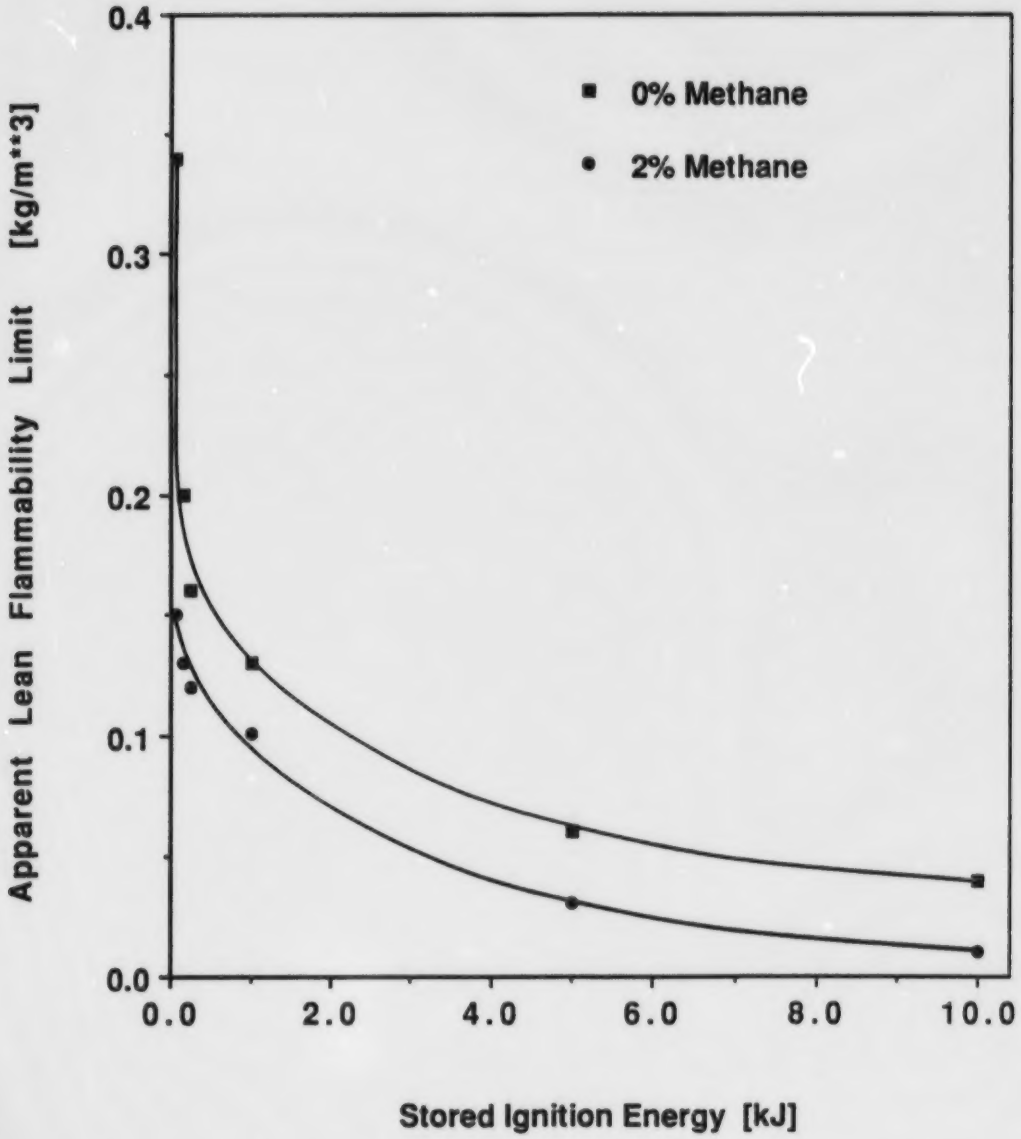


Fig. 4.7 Effect of methane admixture on apparent lean flammability limit of Prince 2 coal.

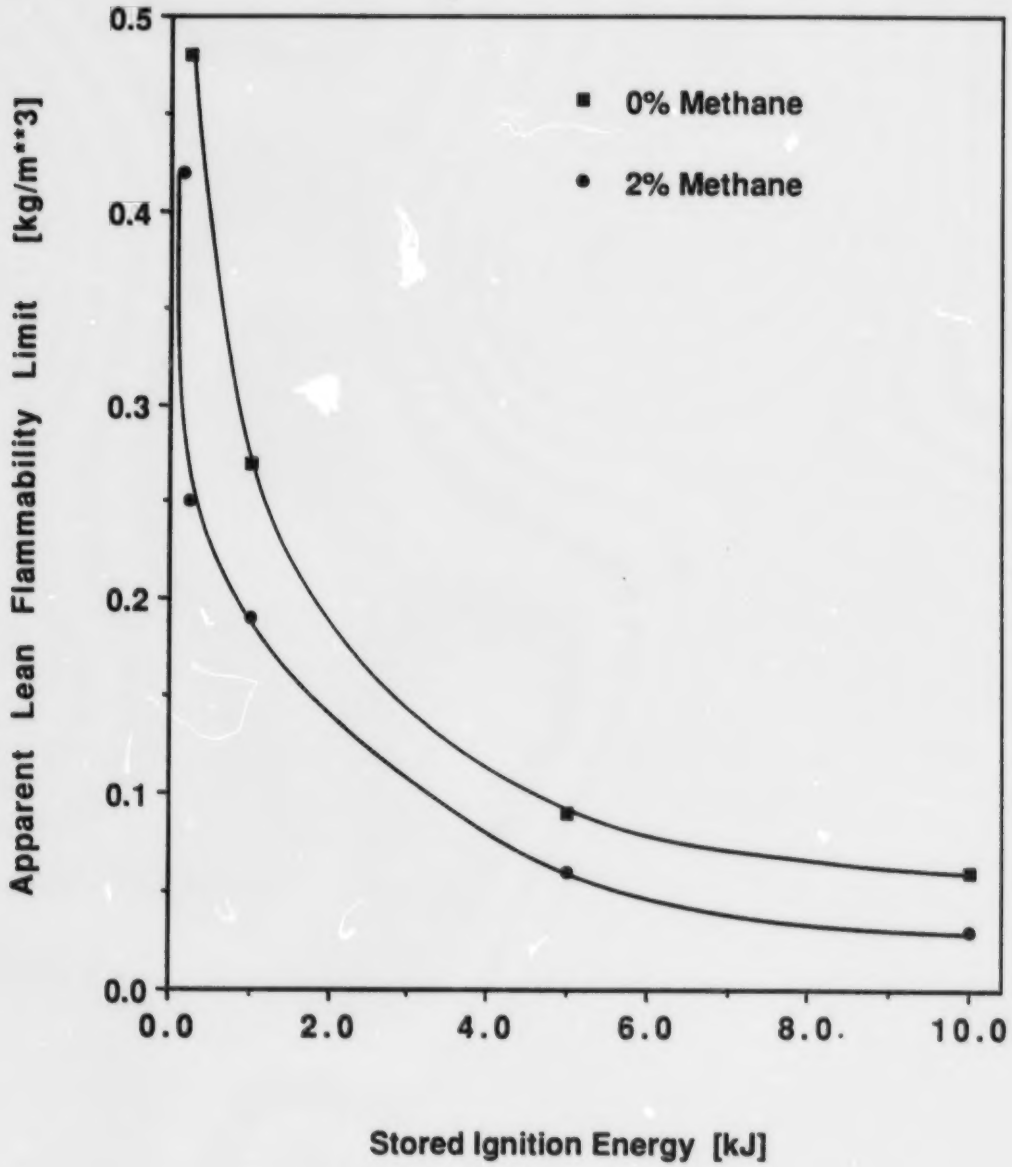


Fig. 4.8 Effect of methane admixture on apparent lean flammability limit of Phalen 1 coal.

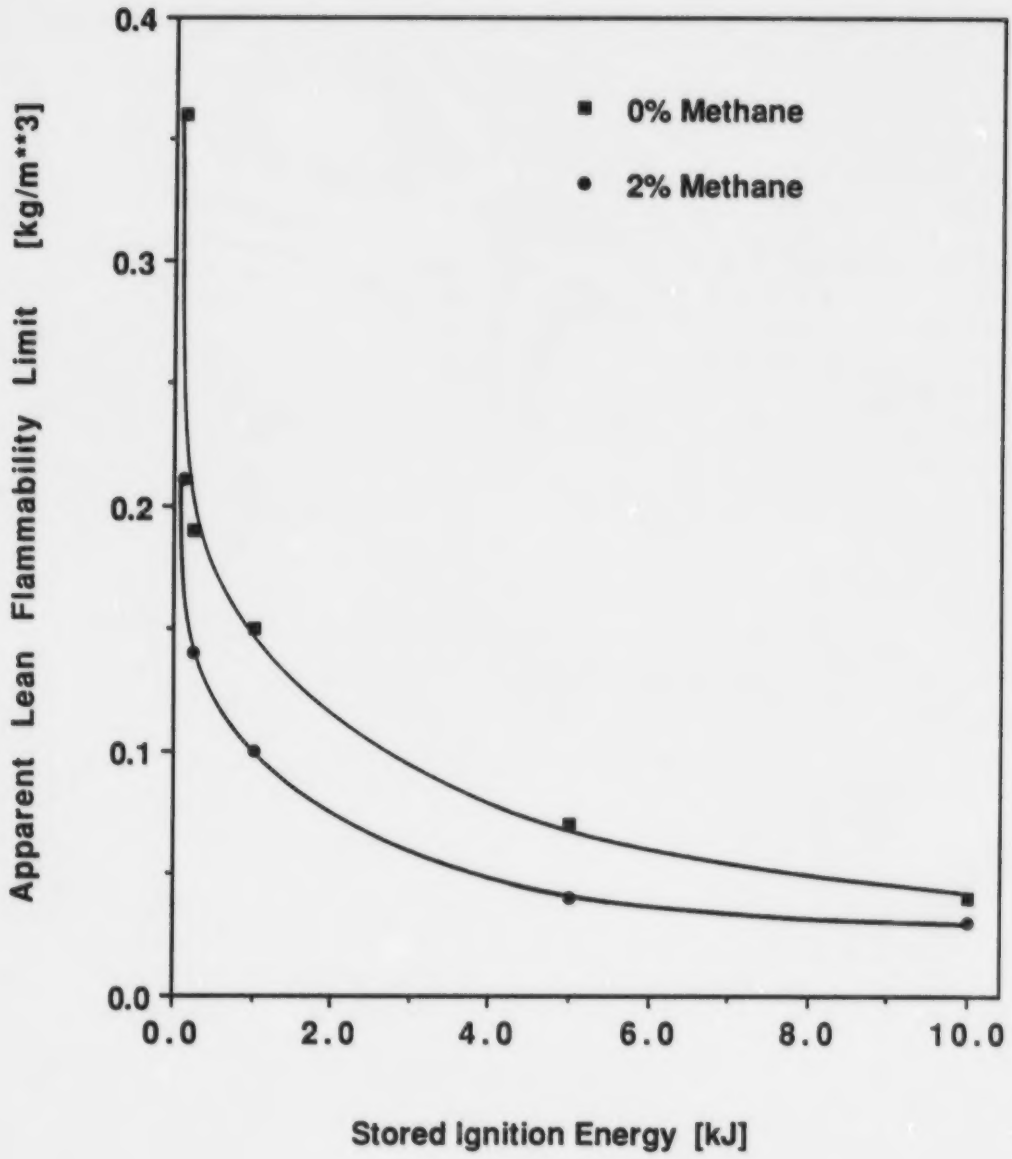


Fig. 4.9 Effect of methane admixture on apparent lean flammability limit of Phalen 2 coal.

limit at a given ignition energy is decreased when methane is present; in other words, less coal dust is required to initiate an explosion. Alternatively, the co-existence of methane with coal dust increases the ignitability of the coal dust; ignition of a given coal dust concentration is attainable with lower energies when methane is present. For each of Figs. 4.6 to 4.9, the region bounded by the 0% - and 2%-methane curves is one of both enhanced flammability and enhanced ignitability.

The lowering of the lean limit with methane admixture is more pronounced at lower ignition energies than at higher energies. This is readily apparent for the Phalen 1 coal which displayed a lean limit of 0.42 kg/m^3 at the 2%-methane level, with a 138-J electric match. However (as previously mentioned), with the same ignition energy and no admixed methane, no explosions were recorded at concentrations up to 1.0 kg/m^3. Methane admixture at this low ignition energy effectively brought the coal dust sample from the non-explosive into the explosive domain (over the range of dust concentrations studied). This may be contrasted with the effect of methane addition on the lean limit of the Phalen 1 coal at the 5-kJ ignition energy level: a decrease in the lean limit from 0.09 kg/m^3 to 0.06 kg/m^3. The data in Figs. 4.6 to Fig. 4.9 also indicate that the influence of methane addition on the lean limit, at low ignition energy, is greater for the larger particle sizes than for the smaller sizes (i.e., Prince 1 compared to Prince 2 and Phalen 1 compared to Phalen 2), and for the lower volatility coals (Phalen) than for the higher volatility coals (Prince).

An explanation for the behaviour described in the previous paragraph can be given in light of the accepted mechanism for flame propagation through a cloud of a volatile-containing dust such as coal. This is usually viewed as a stepwise process in which devolatilization occurs followed by burning of gaseous volatiles. Once devolatilization of a sufficient number of particles occurs, the flame characteristics are dominated by the volatiles with combustion taking place primarily in the gas phase, as suggested by Hertzberg et al. (1986b) and Dixon-Lewis et al. (1987). For low ignition energies, the induction time from ignition to attainment of maximum explosion pressure is long; this is a reflection of the slow rate of devolatilization caused by the low energy input to the system. There is thus an opportunity for the direct addition of volatiles (i.e., methane) to shorten the induction time by participating in the combustion process. On the other hand, induction times

with highly energetic ignition sources are relatively short (of the order of 100 to 200 ms), and methane admixture can be expected to have a less pronounced effect on the lean limit. Larger particles are influenced by methane addition at low ignition energies to a greater extent than smaller particles because of the fact that devolatilization is a surface phenomenon. Smaller particles offer more exposed surface area for devolatilization than do larger particles; the direct addition of methane would supplement the combustion of the rapidly devolatilizing small particles, but not as much as it would for the large particles undergoing devolatilization more slowly.

The decrease in the lean flammability limit with methane admixture can be predicted by Le Chatelier's law, which weights the lean limit for each of the two components (methane and coal dust) according to the percentage of each in the hybrid mixture. This is shown graphically in Figs. 4.10 and 4.11 for the 5-kJ ignitors, using the accepted lean limit for methane of 5% by volume. The linear relationship (dashed line) indicated by Le Chatelier's law separates each graph into two regions: a flammable zone to the right of the line and a nonflammable zone to the left. The applicability of Le Chatelier's law to lower ignition energies can be demonstrated as shown in Fig. 4.12 for the examples of Prince 2 and Phalen 2 with an ignition energy of 138 J.

4.8 Increased Hazard Due to Co-Existence of Methane and Coal Dust

The discussion in the previous section centered on two ways in which the addition of methane, even in a concentration which by itself is nonflammable, to a coal dust/air suspension can significantly increase the explosion hazard over that for a similar dust cloud with no methane present: by lowering the lean flammability limit and by enhancing the ignitability. Other effects of methane admixture to coal dust, in terms of heightened explosibility, have been determined by the present authors in previous work. Although the details are available elsewhere (Amyotte et al., 1991a and 1991b), it seems pertinent to give an outline of the findings here:

(1) For coal dust concentrations less than the optimum concentration, the maximum explosion pressure is somewhat increased by methane admixture; in tests conducted with CBDC coals

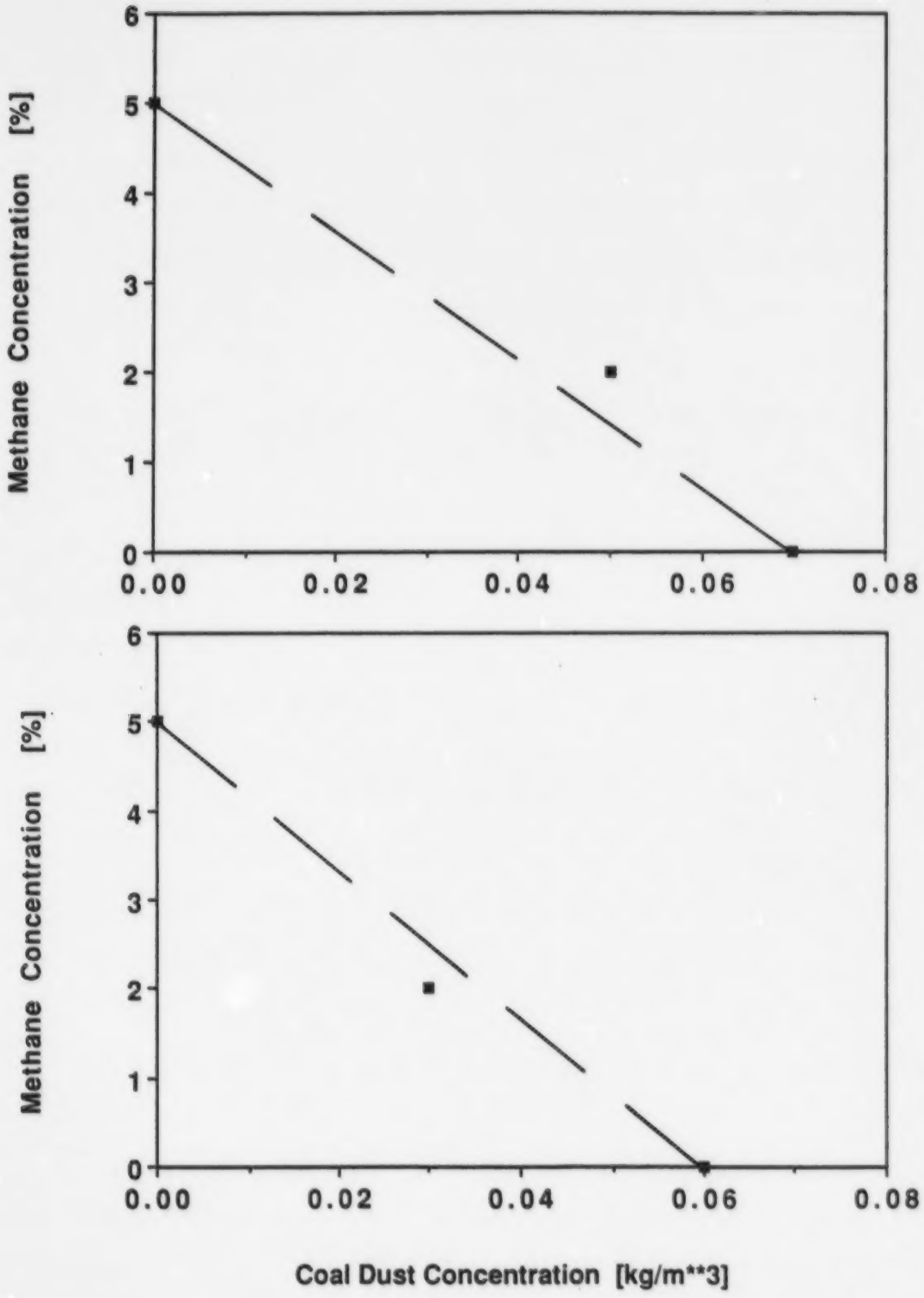


Fig. 4.10 Effect of methane admixture on lean flammability limits of Prince 1 coal (upper plot) and Prince 2 coal (lower plot) for ignition energy of 5 kJ.

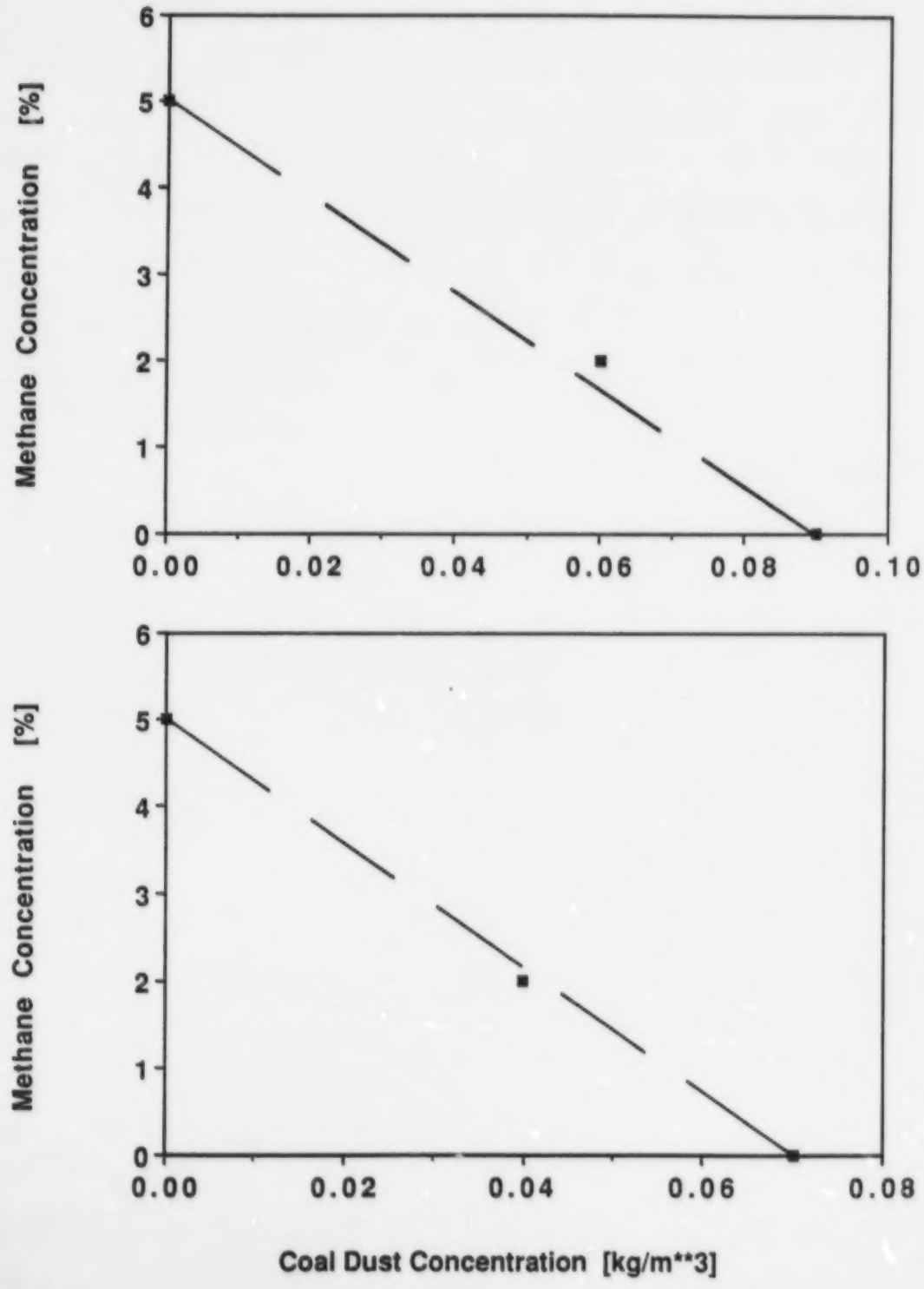


Fig. 4.11 Effect of methane admixture on lean flammability limits of Phalen 1 coal (upper plot) and Phalen 2 coal (lower plot) for ignition energy of 5 kJ.

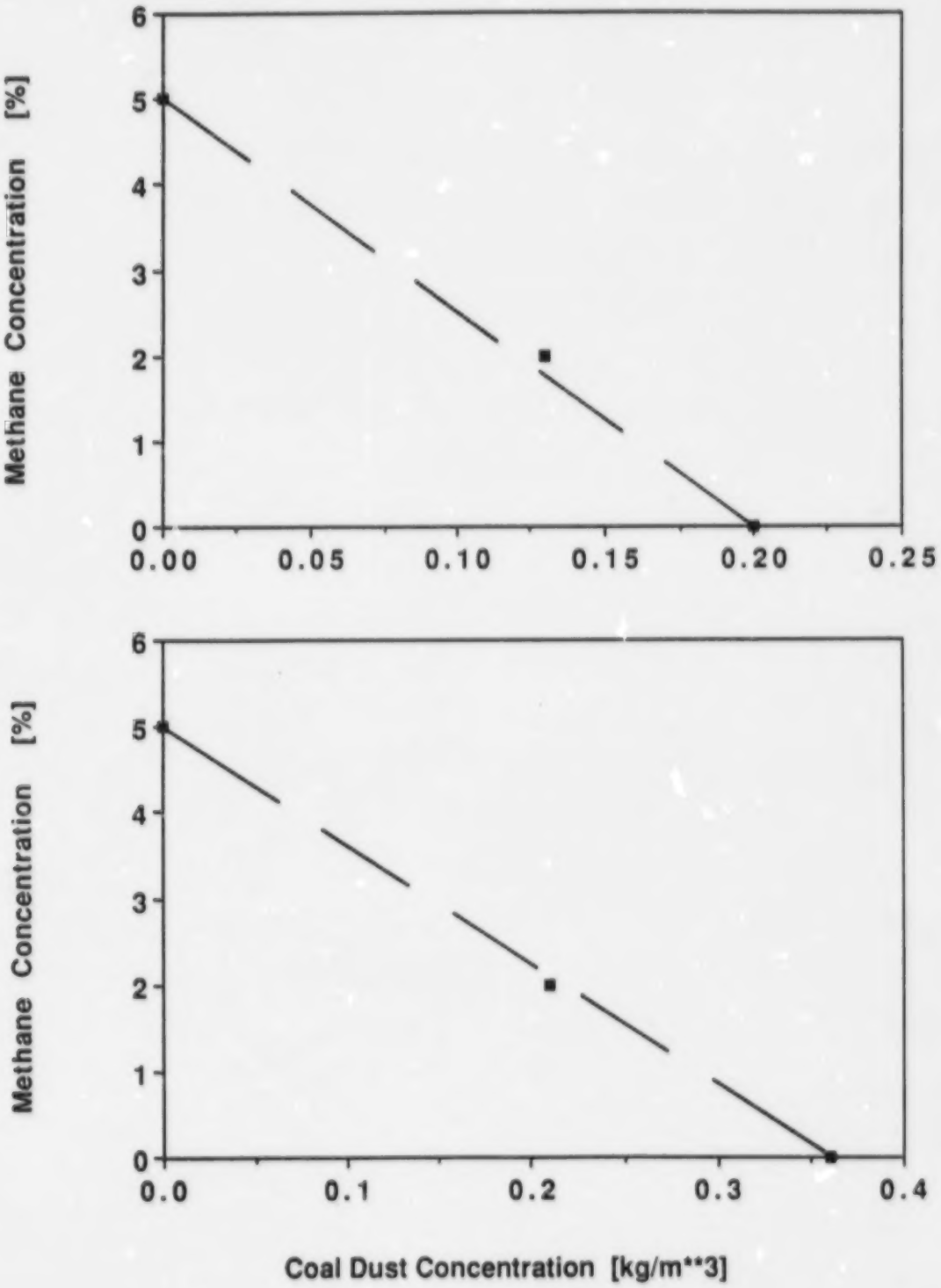


Fig. 4.12 Effect of methane admixture on lean flammability limits of Prince 2 coal (upper plot) and Phalen 2 coal (lower plot) for ignition energy of 138 J.

near the lean flammability limit, P_{max} was at times doubled by the addition of as little as 1% methane by volume. Optimum dust concentration refers to the concentration at which the peak values of P_{max} and $(dP/dt)_{max}$ are recorded; a typical value for CBDC coals is about 0.5 kg/m^3. The influence of methane admixture becomes less significant as the coal dust concentration approaches the optimum concentration, until at high dust loadings (greater than optimum), methane has little, if any, effect on the maximum explosion pressure.

(2) The maximum rate of pressure rise undergoes a significant increase with methane addition at all coal dust concentrations. The burning velocity of the mixture and hence the flame speed increase accordingly.

Methane admixture has a more significant effect on $(dP/dt)_{max}$ than on P_{max}, with this effect being apparent over a wider range of dust concentrations for $(dP/dt)_{max}$ than for P_{max}.

(3) With methane addition, the peak values of P_{max} and $(dP/dt)_{max}$ occur at dust concentrations which are less than those for coal dust alone. In tests conducted with CBDC coals, a typical value was a decrease in coal dust concentration of ~0.1 kg/m^3 at the 1%-methane level. In these tests, the shift in optimum dust concentration was more apparent at 2% methane than at 1%.

(4) The peak values of $(dP/dt)_{max}$ for coal dust alone are exceeded by methane/coal dust mixtures at leaner dust concentrations.

As previously mentioned, the combustion of a volatile dust is a stepwise process in which devolatilization occurs followed by burning of gaseous volatiles; the peak value of maximum rate of pressure rise corresponds to the burning of a near-stoichiometric concentration of these volatiles. One of the primary effects of methane admixture, therefore, is to enable the fuel/air mixture to attain a stoichiometric or near-stoichiometric concentration of combustible volatiles at lower dust concentrations.

(5) It is well-established that an effect of methane addition is to increase the amount of inert material required to suppress an explosion. For example, in the coal mining industry, the

presence of methane necessitates the use of additional rock dust for inerting. A legal requirement in Canada is 5% more rock dust for each 1% by volume methane; at the high levels of rock dust required to inert coal dust alone, an additional 5% is a significant mass of inert material.

These points, together with the comments in the previous section, serve to illustrate the deleterious effects of methane admixture to coal dust. Coal dust alone represents a significant explosion hazard; clearly, this hazard is magnified by the addition of methane to the oxidizing atmosphere.

4.9 Effect of Coal Particle Size on Lean Flammability Limit

The effects of a change in coal particle size (or more properly, particle size distribution), for coals having nearly the same volatile content, are shown in Figs. 4.13 to 4.16. For each methane percentage, the apparent lean flammability limit at a given ignition energy is decreased with a decrease in mass mean diameter of the parent coal. This particle size dependence of the lean flammability limit is consistent with previous work (Amyotte et al., 1991a) which utilized coals having similarly broad particle size distributions. From an ignitability perspective, ignition of a given coal dust concentration is attainable with lower energies when there is a reduction in coal particle size.

The lowering of the lean limit with a reduction in coal particle size is more pronounced at lower ignition energies than at higher energies. This can clearly be seen for the Phalen coals with no methane present. As noted previously, no explosions were recorded (at coal dust concentrations up to 1.0 kg/m^3) for the Phalen 1 coal with a 138-J ignition energy. However, the Phalen 2 coal, with the same ignitor, displayed a lean limit of 0.36 kg/m^3. This may be contrasted with the effect of coal particle size on the lean limit of the Phalen coals at the 5-kJ ignition energy level: a decrease in the lean limit from 0.09 kg/m^3 (Phalen 1) to 0.07 kg/m^3 (Phalen 2). The data in Figs. 4.13 to 4.16 also indicate that the influence of coal particle size on the lean limit, at low ignition energy, is

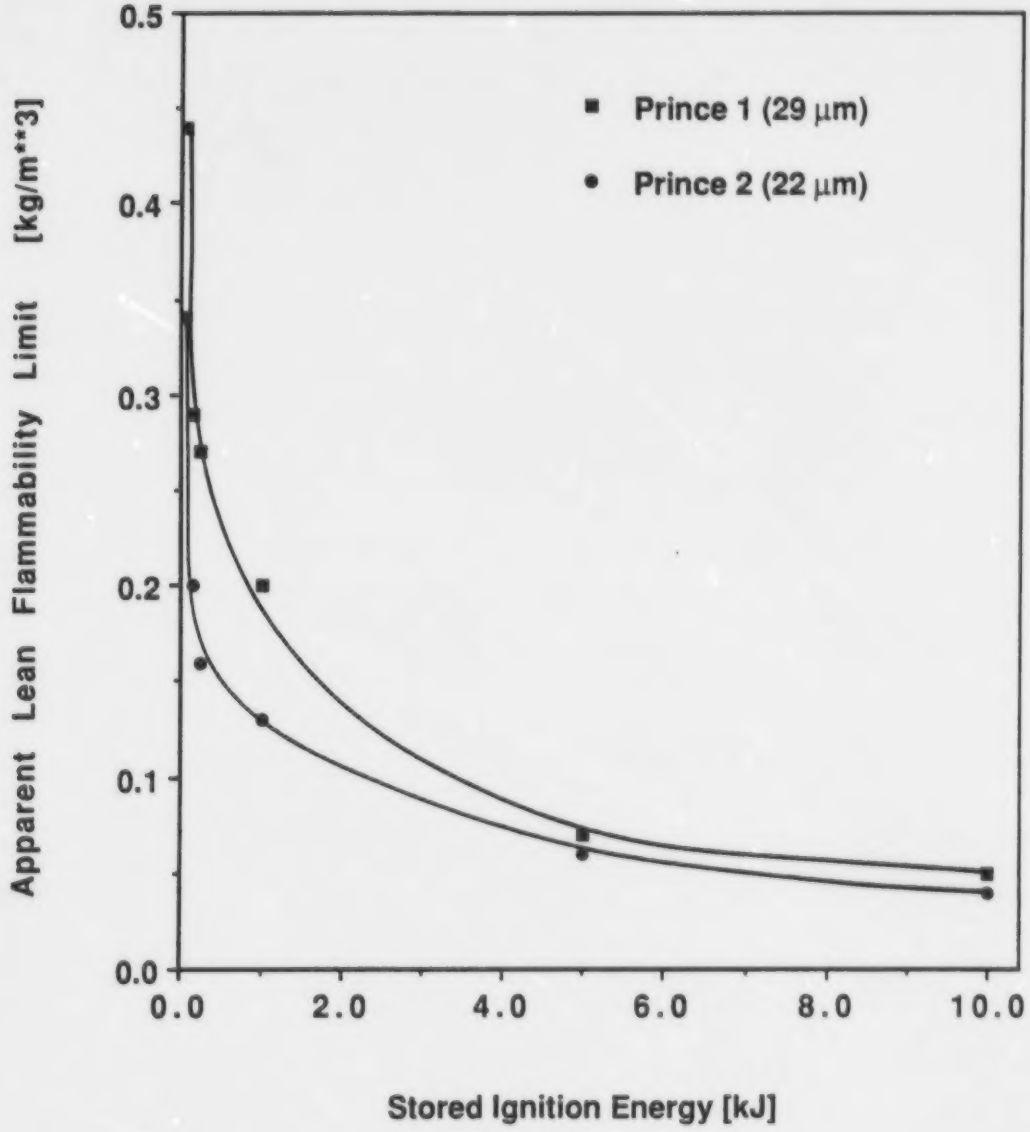


Fig. 4.13 Effect of coal particle size on apparent lean flammability limit of Prince coals (0% methane).

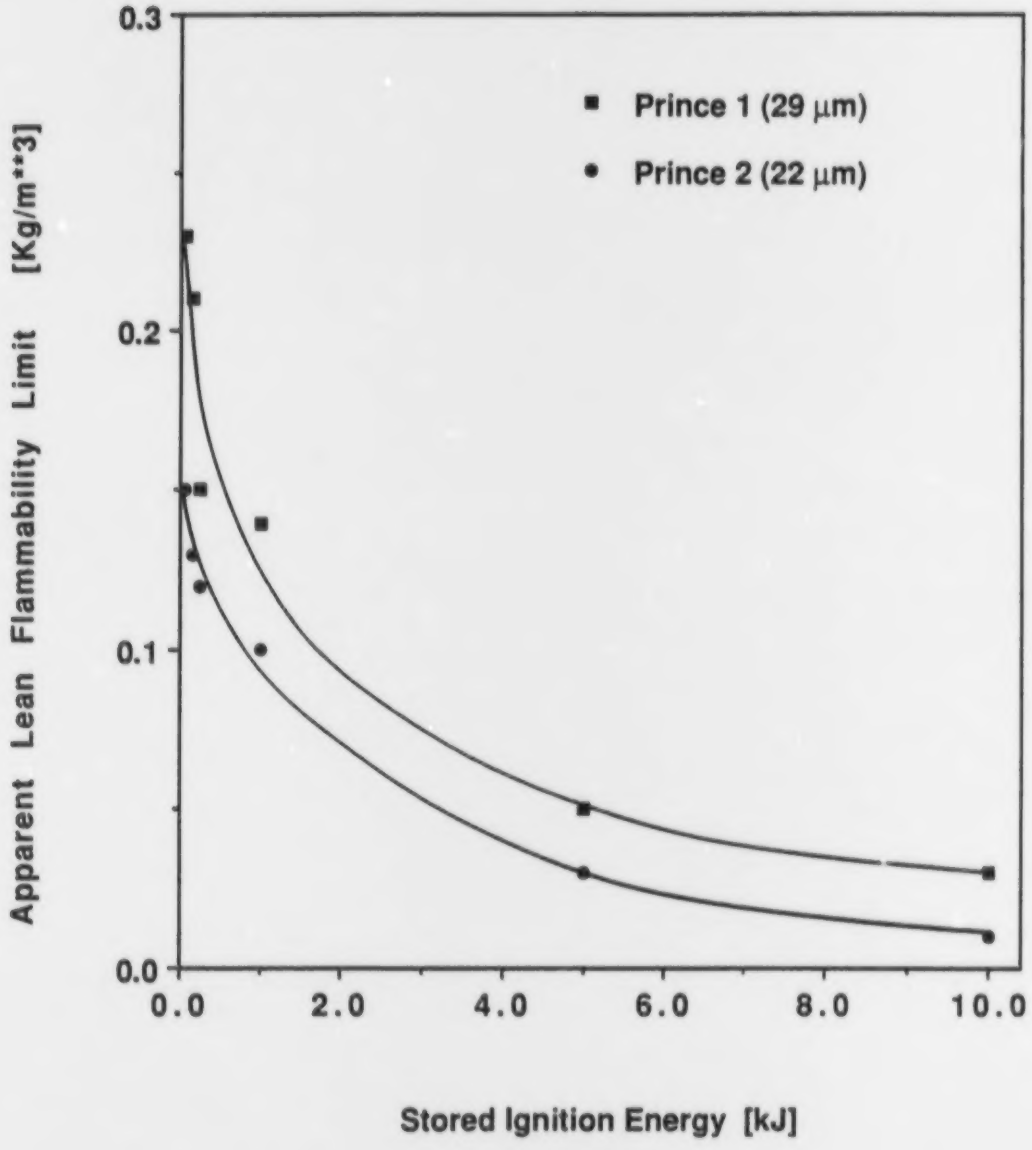


Fig. 4.14 Effect of coal particle size on apparent lean flammability limit of Prince coals (2% methane).

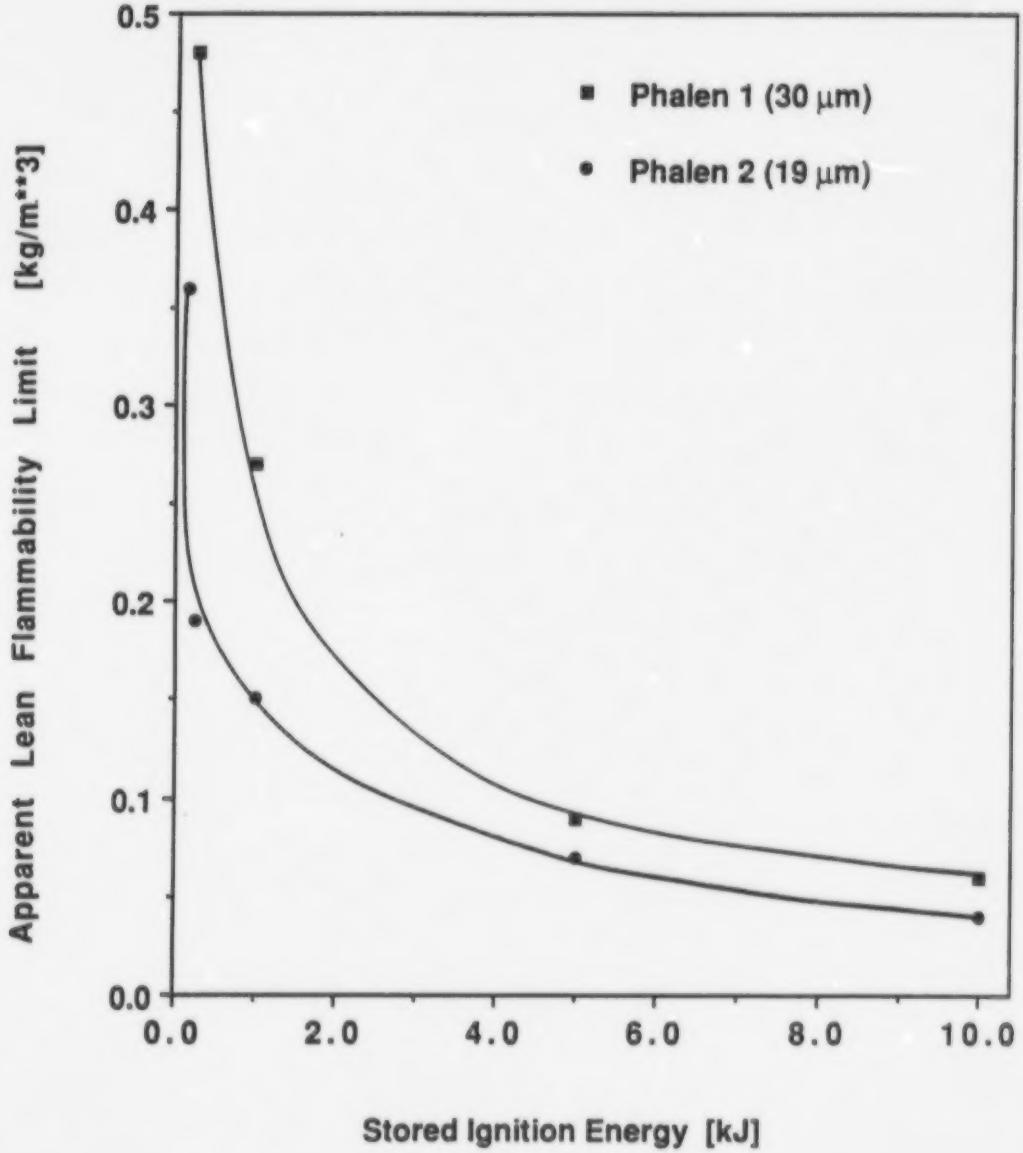


Fig. 4.15 Effect of coal particle size on apparent lean flammability limit of Phalen coals (0% methane).

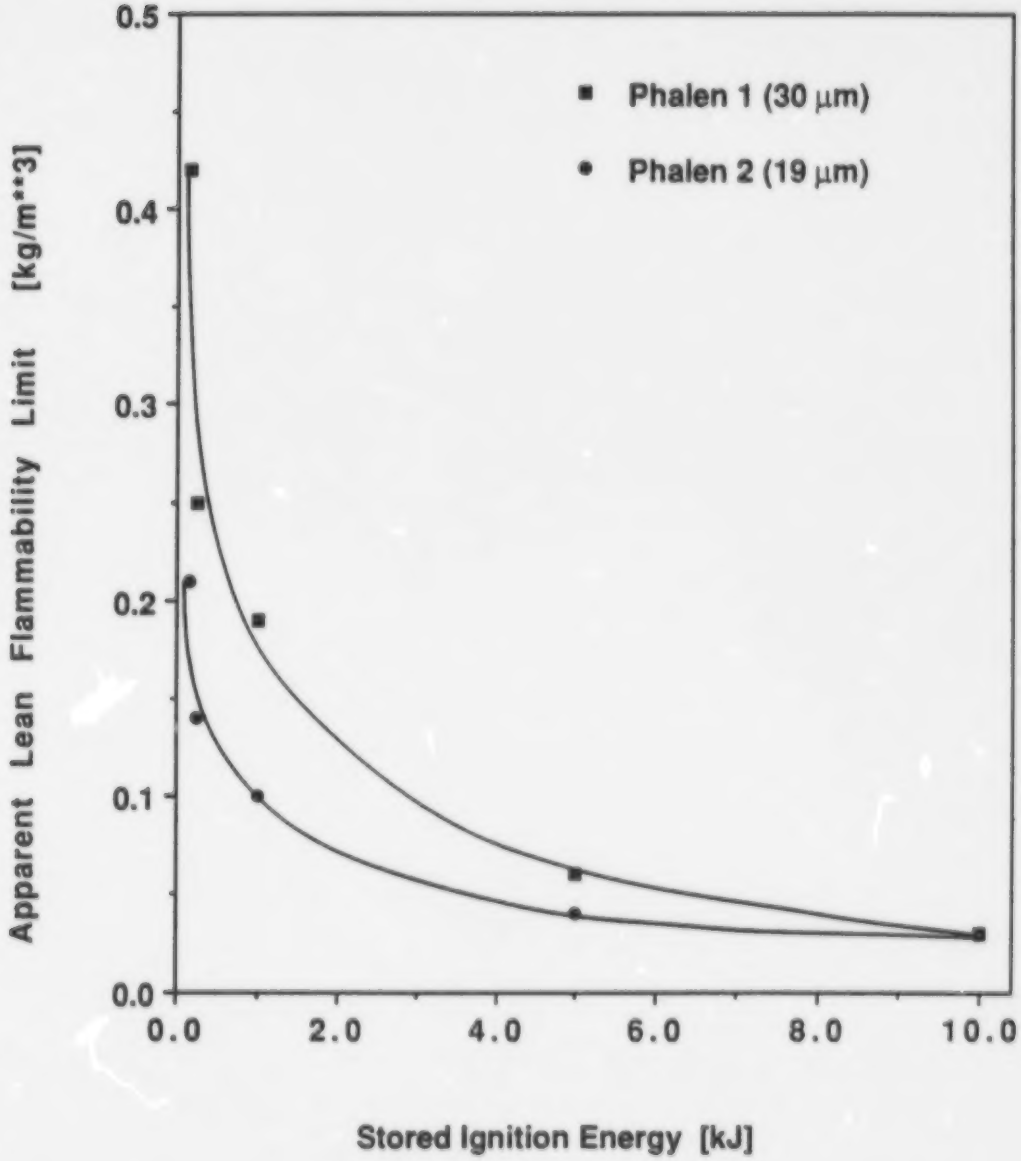


Fig. 4.16 Effect of coal particle size on apparent lean flammability limit of Phalen coals (2% methane).

greater in the absence rather than the presence of methane, and for the lower volatility coals (Phalen) than for the higher volatility coals (Prince).

These findings are consistent with the discussion on methane admixture in section 4.7, and again relate to the increase in rate of devolatilization which accompanies a decrease in mass mean diameter. Such a decrease leads to an increase in the number of fine particles, which is nearly equivalent to adding a combustible gas because of the rapid rate of devolatilization of the fines. The similarities between Figs. 4.13 to 4.16 (showing effect of particle size) and Figs. 4.6 to 4.9 (showing effect of methane admixture) are, therefore, not surprising. Comparison of Figs. 4.13 and 4.6 shows that reducing the mass mean diameter from 29 μm (Prince 1) to 22 μm (Prince 2) is almost equivalent to adding 2% methane to the oxidizing atmosphere for a parent coal having a mass mean diameter of 29 μm (Prince 1). Similarly, comparison of Figs. 4.15 and 4.8 shows that reducing the mass mean diameter from 30 μm (Phalen 1) to 19 μm (Phalen 2) is nearly equivalent to adding 2% methane to the oxidizing atmosphere for a parent coal having a mass mean diameter of 30 μm (Phalen 1).

4.10 Effect of Coal Volatile Content on Lean Flammability Limit

The effects of a change in coal volatile content, for coals having nearly the same particle size distribution, are shown in Figs. 4.17 to 4.20. For each methane percentage, the apparent lean flammability limit at a given ignition energy is decreased with an increase in coal volatile content; this behaviour is consistent with that previously observed (Amyotte et al., 1991a). With respect to ignitability, the results show that ignition of a given coal dust concentration is possible with lower energies when the coal volatile content is increased.

Several other observations can be made with regard to Figs. 4.17 to 4.20. These are similar in nature to those discussed in sections 4.7 (methane admixture) and 4.9 (coal particle size), and are also consistent with a description of coal dust flame propagation by combustion of devolatilization products:

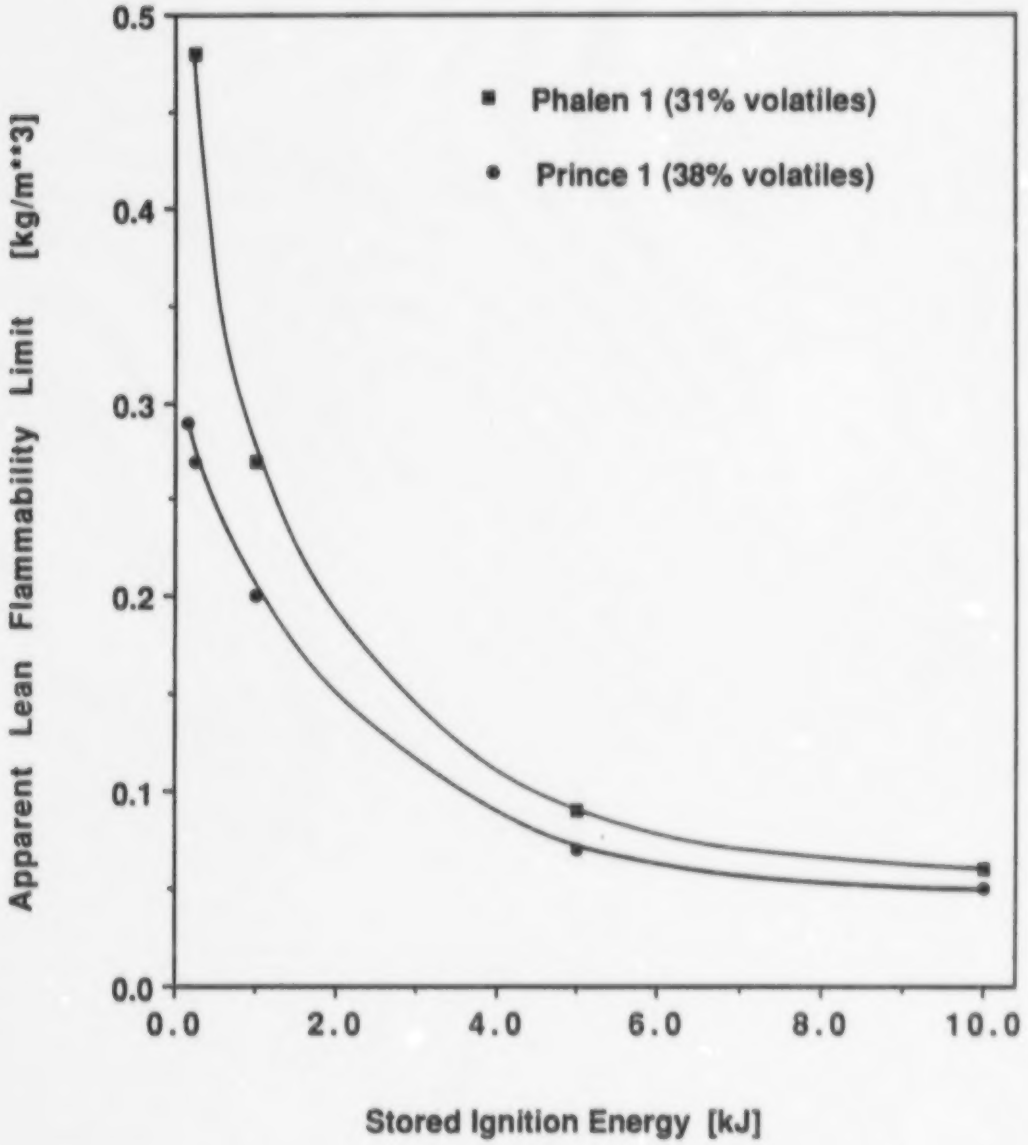


Fig. 4.17 Effect of coal volatile content on apparent lean flammability limit of larger particle size coals (0% methane).

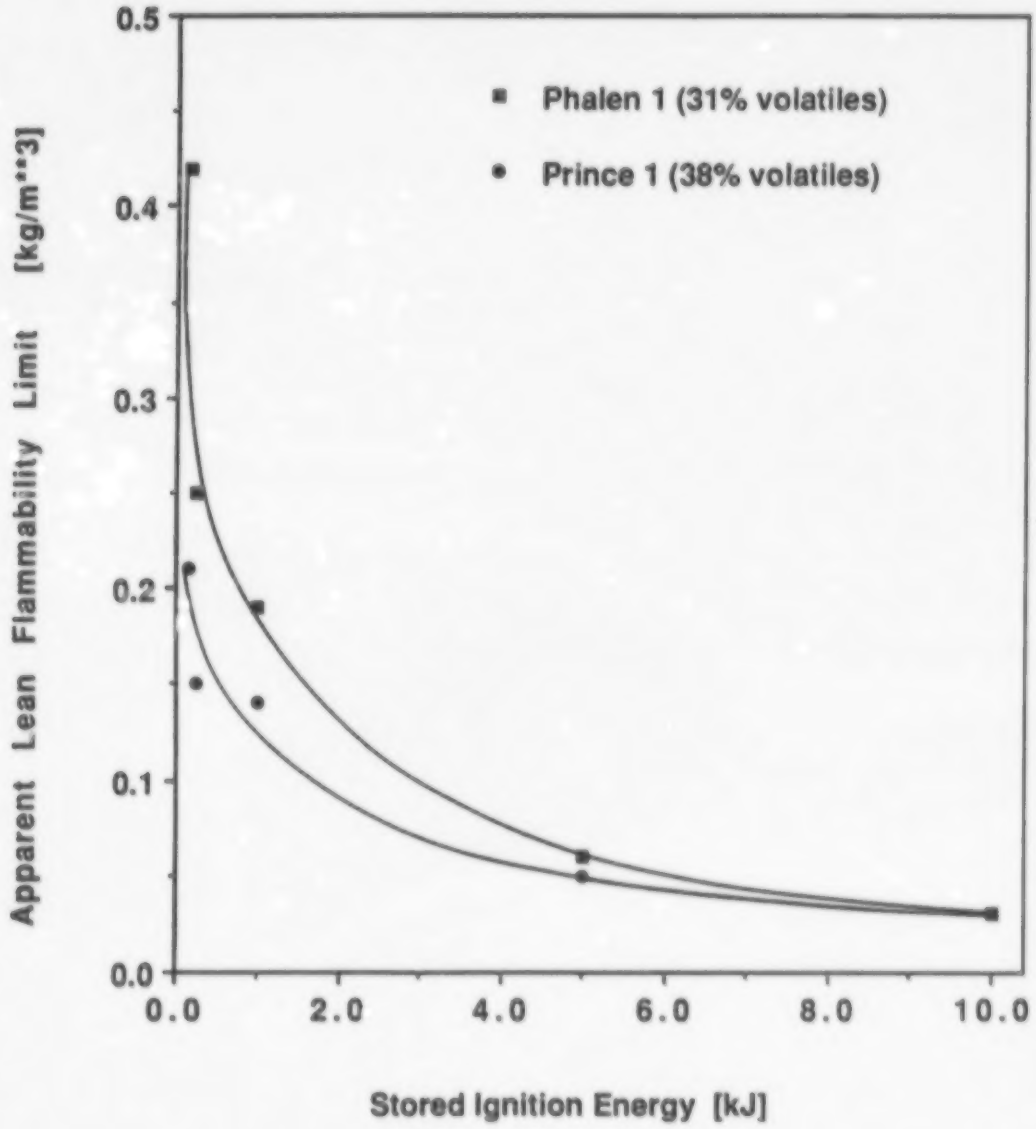


Fig. 4.18 Effect of coal volatile content on apparent lean flammability limit of larger particle size coals (2% methane).

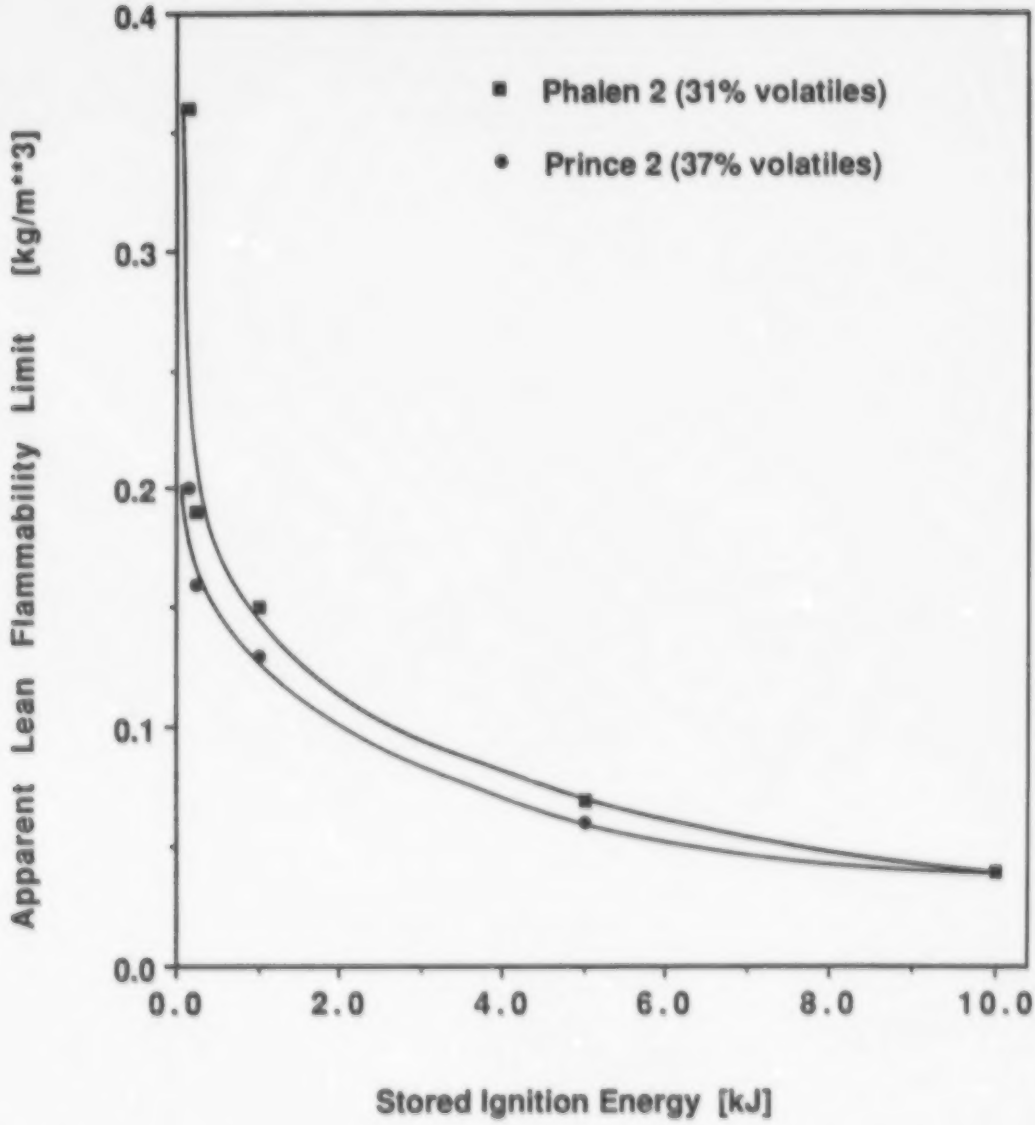


Fig. 4.19 Effect of coal volatile content on apparent lean flammability limit of smaller particle size coals (0% methane).

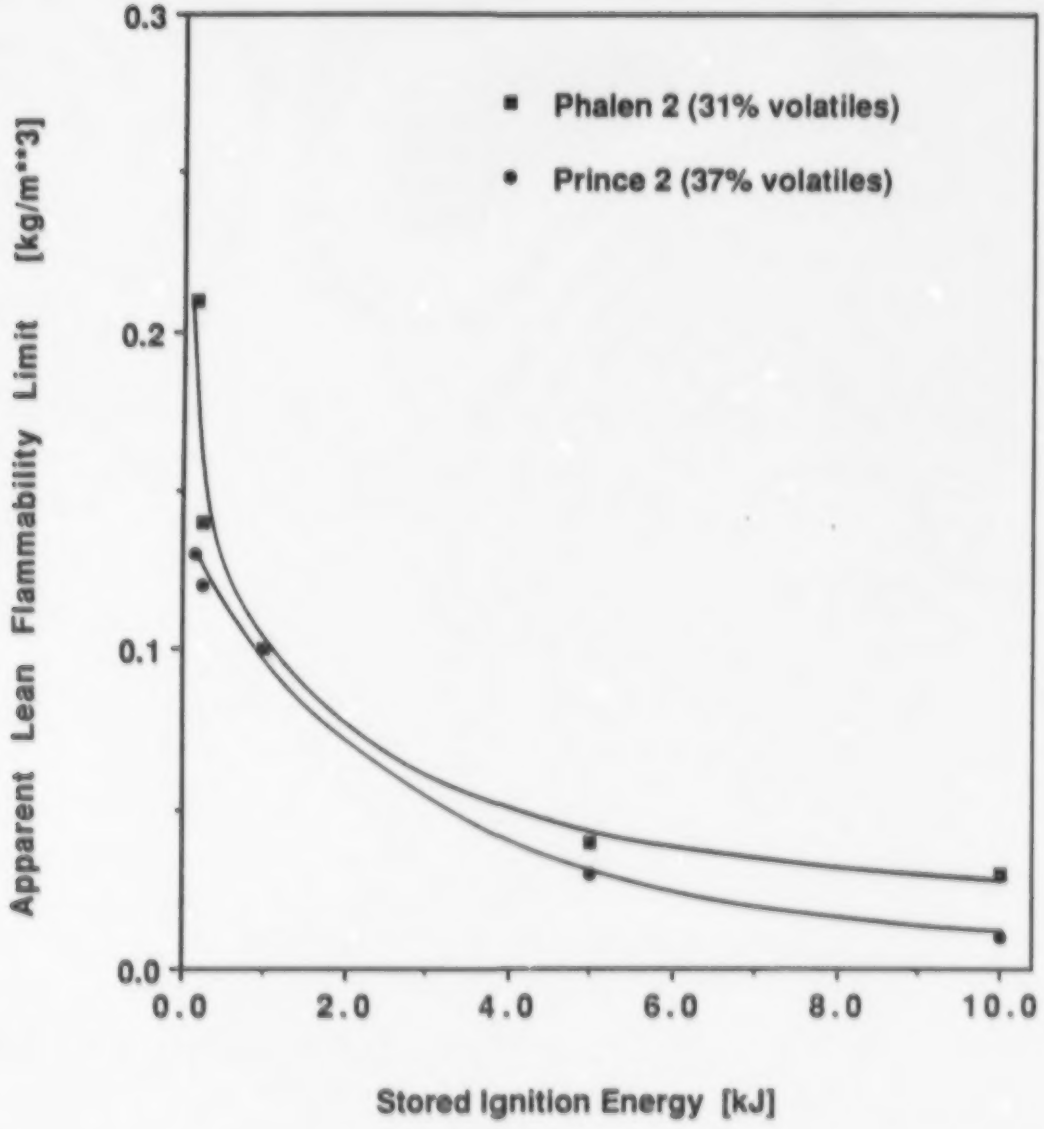


Fig. 4.20 Effect of coal volatile content on apparent lean flammability limit of smaller particle size coals (2% methane).

(1) The lowering of the lean limit with an increase in coal volatile content is more pronounced at lower ignition energies than at higher energies.

(2) The influence of coal volatile content on the lean limit, at low ignition energy, is greater in the absence rather than the presence of methane.

(3) The influence of coal volatile content on the lean limit, at low ignition energy, is greater for the larger particle sizes (Prince 1 and Phalen 1) than for the smaller sizes (Prince 2 and Phalen 2).

Some quantification of the flame propagation model for volatile-containing dusts can be obtained by examining the product of the lean limit concentration (taken for an ignition energy of 5 kJ) and the combustible volatile yield (i.e., coal volatile content). According to Hertzberg et al. (1986a), this product should be constant if flame propagation is by gas-phase burning of devolatilization products. Table 4.1 shows that this is indeed the case for the current results.

4.11 Inerting Tests

The inerting tests were conducted to examine the relative effectiveness of limestone, dolomite and magnesite with respect to suppression of coal dust explosions. A single coal dust concentration of 0.5 kg/m^3 was used for the Prince 2 sample with no methane present and an ignition energy of 5 kJ. This coal dust concentration was used because, as mentioned in section 4.8, it is a typical value of the optimum dust concentration for CBDC coals. In other words, it is representative of the most hazardous coal dust concentration in terms of blast effects (P_{max} and $(dP/dt)_{max}$).

The results shown in Figs. 3.9 to 3.12 are consistent with those obtained in more exhaustive studies of rock dusting requirements (Amyotte et al., 1991b and Cashdollar and Hertzberg, 1989). The maximum explosion pressure undergoes only a slight decrease with an increase in rock dust percentage, up to near the inerting level (the percentage of rock dust required to inert the explosive mixture). At this point, there is a sudden and rapid drop in P_{max}. The

Table 4.1 Comparison of products of lean flammability limit and coal volatile content (for a given particle size and methane concentration).

(1) Coal Type and Size	(2) Methane Concentration [%]	(3) Lean Limit at 5-kJ Level [kg/m^3]	(4) Coal Volatile Content [%]	(5) Product of Columns (3) and (4)
Prince 1	0	0.07	37.5	2.6
Phalen 1	0	0.09	31.0	2.8
Prince 1	2	0.05	37.5	1.9
Phalen 1	2	0.06	31.0	1.9
Prince 2	0	0.06	36.5	2.2
Phalen 2	0	0.07	30.9	2.2
Prince 2	2	0.03	36.5	1.1
Phalen 2	2	0.04	30.9	1.2

maximum rate of pressure rise, on the other hand, exhibits a fairly smooth and continuous decrease from the onset of rock dust addition.

Of primary interest in this work was the inerting level; the criteria used to specify this level were the same P_{max} and $(dP/dt)_{max}$ criteria as in the lean limit work ($P_{max} \geq 2$ bar (absolute) and $(dP/dt)_{max} \cdot V^{1/3} \geq 1.5$ bar • m/s). The inerting requirements thus obtained are shown in Table 4.2. The results are presented in three ways: as the percentage of rock dust in the total solids mixture (rock dust plus coal dust), as the percentage of incombustibles in the total solids mixture, and as the ratio of rock dust to coal dust (inerting ratio). The total incombustible content, or TIC, is composed of the rock dust and the ash and moisture in the coal.

4.11.1 Effect of rock dust type

As mentioned in the Introduction, rock dusts are generally viewed as thermal inhibitors. Nagy (1981) comments that although the quenching mechanism of rock dust is not fully understood, it is believed to arrest flame propagation by absorption of thermal energy from the heated gases and by absorption of radiant energy, thus reducing the preheating of unburnt particles. If the rock dust decomposition temperature (and hence possible chemical inhibition) was to pay a role, one would expect the increasing order of inerting effectiveness to be: magnesite, dolomite, limestone. The decomposition temperatures are 350°C, 750°C and 825°C, respectively.

The results in Table 4.2 show that this is not the case, however. The inerting levels for the three rock dusts having about the same particle size distribution (limestone, dolomite (regular grind) and magnesite) are identical. The relative proportions of $CaCO_3$ and $MgCO_3$ in each rock dust do not influence the amount of inert material needed to suppress an explosion.

It is possible, though, that some devolatilization of the magnesite does occur over the short duration of a coal dust explosion in the 26-L vessel. This statement is made based on Figs. 4.21 and 4.22 which show the effect of rock dust type and concentration on P_{max} and $(dP/dt)_{max}$. For clarity, only the dolomite (regular grind) and magnesite data have been plotted. There is some separation between the curves for the two materials over a wide range of rock dust concentrations.

Table 4.2 Rock dust inerting requirements for Prince 2 coal (0% methane, 5-kJ ignition energy).

Rock Dust Type	Rock Dust Concentration [%]	Total Incombustible Content [%]	Inerting Ratio
Limestone	84	86	5.3
Dolomite (regular grind)	84	86	5.3
Dolomite (-300 mesh)	74	77	2.8
Magnesite	84	86	5.3

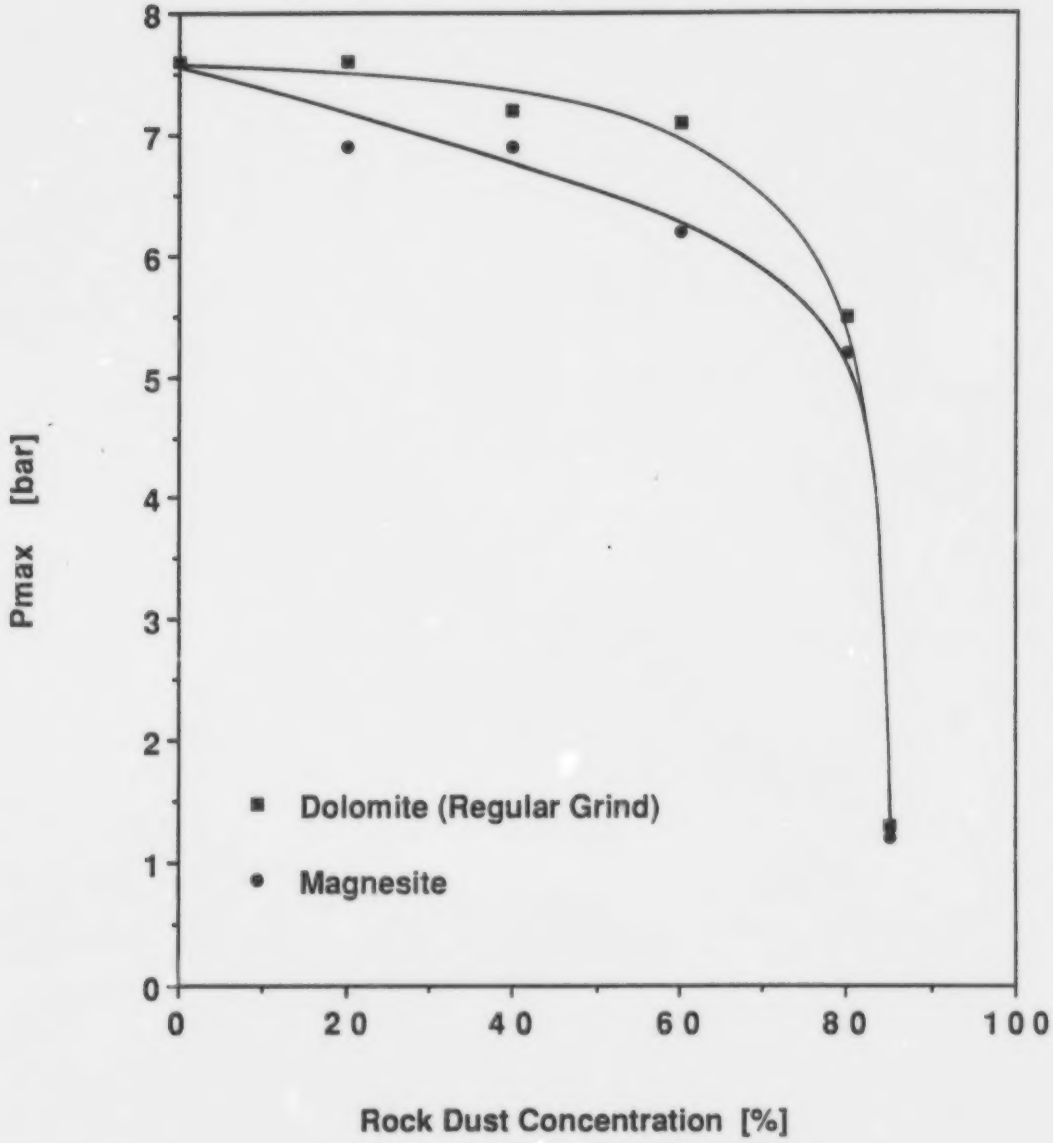


Fig. 4.21 Effect of rock dust type and concentration on P_{max} of Prince 2 coal (0% methane, 5-kJ ignition energy).

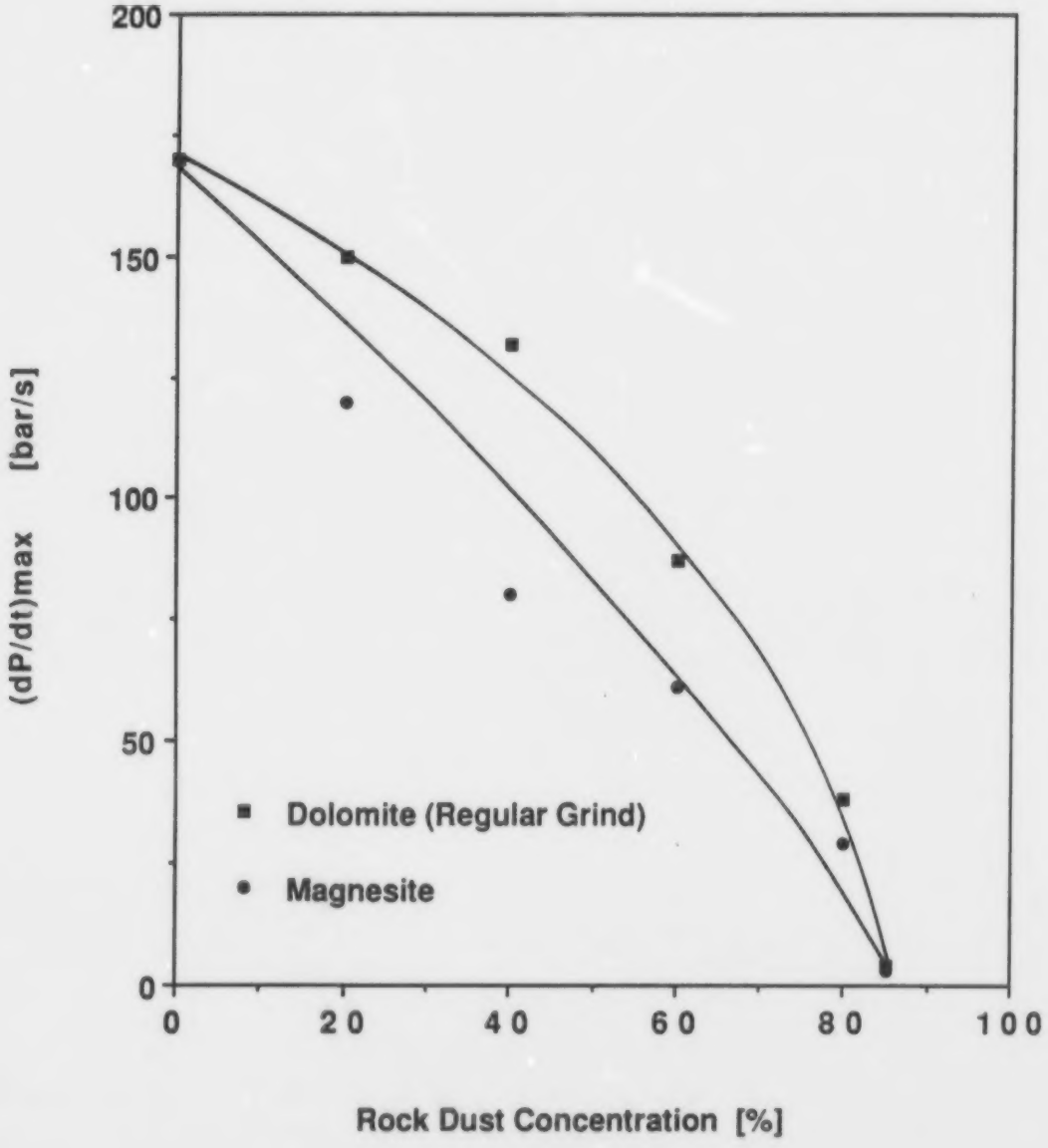


Fig. 4.22 Effect of rock dust type and concentration on $(dP/dt)_{max}$ of Prince 2 coal (0% methane, 5-kJ ignition energy).

This separation, however, disappears near the inerting level and the result is an inerting ratio of 5.3 in each case. It must be stressed that only limited testing was conducted in this portion of the current study; this is an area, though, where further investigation may be merited.

4.11.2 Effect of rock dust particle size

Table 4.2 and also Figs. 4.23 and 4.24 demonstrate that the particle size of the rock dust has a significant effect on the amount required for inerting. This was also observed by Hertzberg and Cashdollar (1989); the explanation provided by these researchers was that finer rock dusts are most likely more effective heat sinks. From a practical perspective, the results show that the mass of dolomite needed for explosion suppression was reduced almost in half by a reduction in dolomite mass mean diameter from 30 μm (regular grind) to 18 μm (-300 mesh). Again, this portion of the current study was conducted with only limited testing. This is another area, however, where further study may be warranted.

4.12 Applicability to Coal Mining Industry

In the final section of this chapter the applicability of the current results to the coal mining industry is discussed. This is done by first considering the key test parameters of turbulence level, methane concentration, and ignition source and energy. The discussion then shifts to a brief examination of two properties of the test material: coal particle size and coal ash content. Most of these points have been addressed in previous work (Amyotte et al., 1991a and 1991b). They are worth repeating here, however, because of the importance of industrial applicability.

4.12.1 Turbulence level

Turbulence plays a large role in determining the explosion characteristics of a dust (particularly $(dP/dt)_{max}$) and is, therefore, a dominant concern in dust explosion research (Amyotte et al., 1988). In closed-vessel testing, with an air blast used to disperse the dust throughout the vessel, some degree of turbulence will always be present in the test apparatus before ignition.

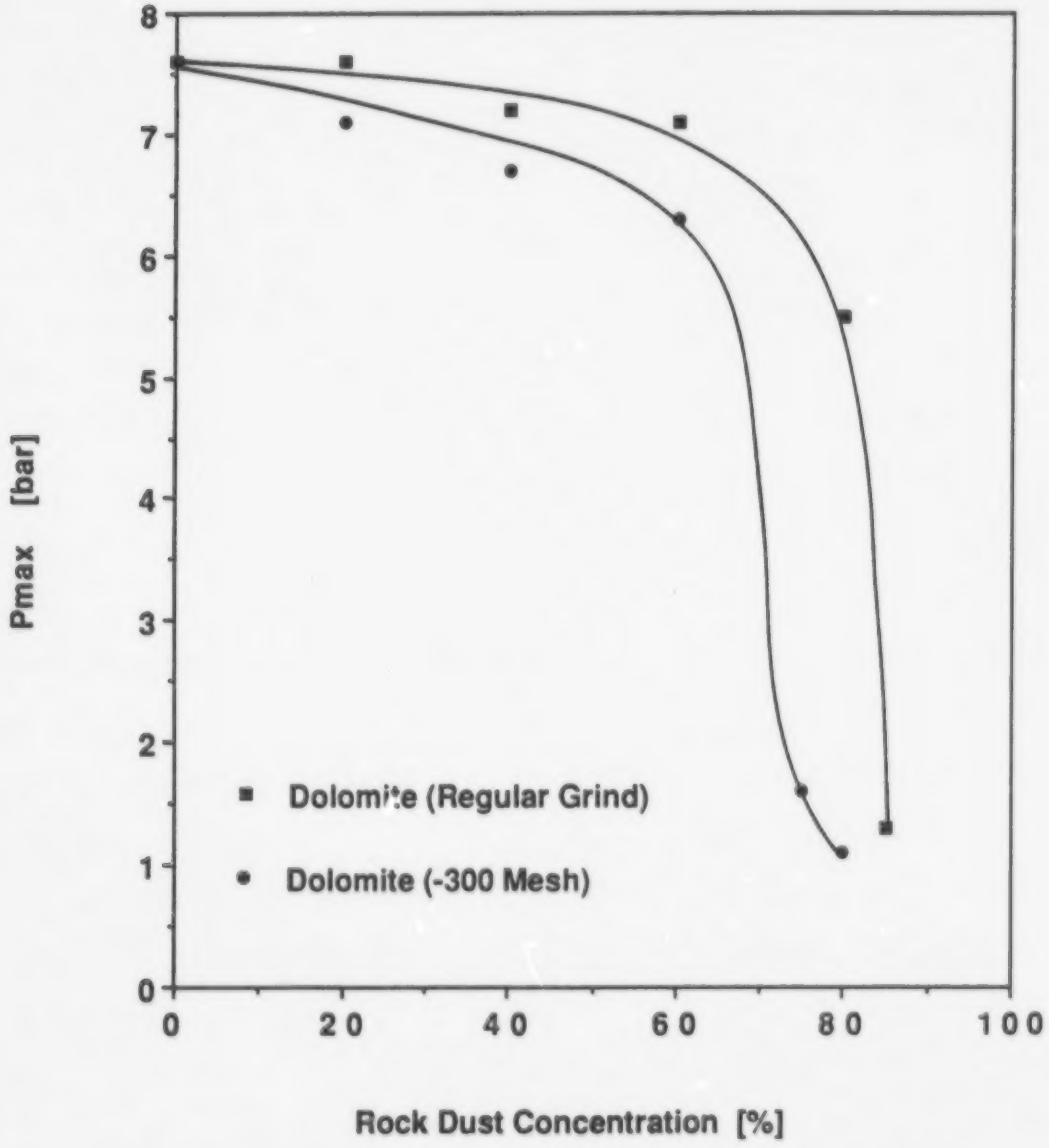


Fig. 4.23 Effect of rock dust particle size and concentration on P_{max} of Prince 2 coal (0% methane, 5-kJ ignition energy).

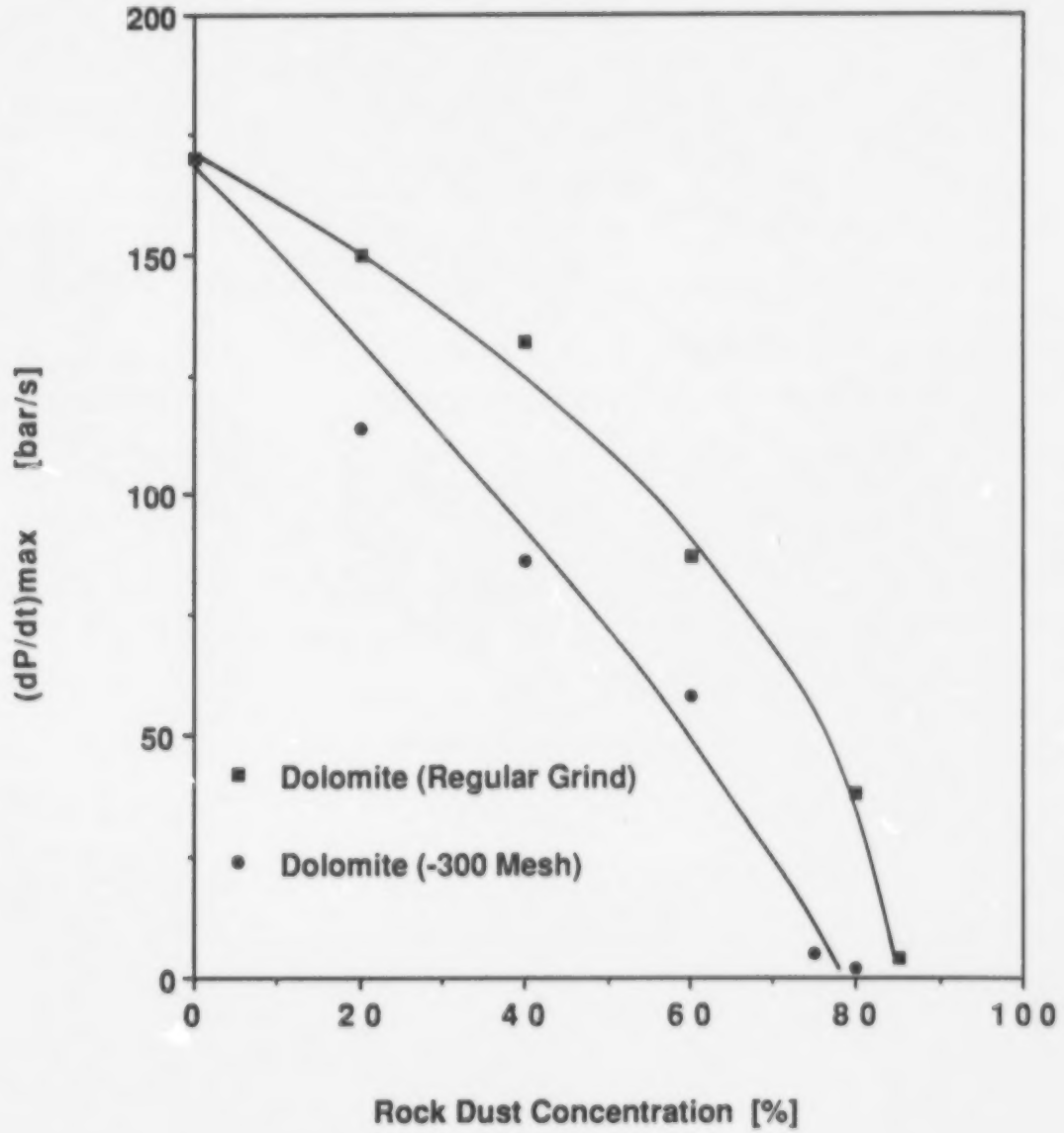


Fig. 4.24 Effect of rock dust particle size and concentration on $(dP/dt)_{max}$ of Prince 2 coal (0% methane, 5-kJ ignition energy).

Factors which strongly influence the turbulence level in dust explosion testing include the dispersion reservoir volume, the dispersing air pressure, the ignition delay time and the dispersion nozzle itself. In the current work, these parameters were 1 L, 13.8 bar (g), 410 ms and the U.S. Bureau of Mines perforated design, respectively.

The choice of these values, particularly the dispersing air pressure and ignition delay time, was governed by the desire to obtain measurements of maximum explosion pressure and maximum rate of pressure rise (and hence lean flammability limits and inerting ratios) that were comparable to those determined at the U.S. Bureau of Mines in a 20-L test vessel for Pittsburgh seam bituminous coal dust. The U.S. Bureau of Mines small-scale results have been consistently shown to compare favourably with the data from large-scale testing at the Bureau's Bruceton and Lake Lynn Experimental Mines (Cashdollar et al., 1987). Thus, the rationale for setting the turbulence level in the present work was to give the test results some relevance to what would be expected in an actual mine setting.

4.12.2 Methane concentration

A quantitative assessment of the hazards associated with hybrid mixtures of methane and coal dust is relevant to the safe operation of deep, underground mines (such as those operated by CBDC). Monitoring and removal (by ventilation air) of methane from these mines are essential. In practice, the cutting machinery in the mines automatically shuts down when the methane level reaches 1.25 volume %; at 2.25 volume % methane, evacuation of personnel commences. The methane concentration of 2% used in the current study is, therefore, of direct relevance to the coal mining industry.

4.12.3 Ignition source and energy

A variety of ignition sources and energies were used in this work. These can be generalized as ranging from electric sparks (of the order of several J), through electric matches (of the order of 100 J), to chemical ignitors (of the order of hundreds of J to several kJ). Although a one-to-one

correlation is not possible, it is felt that this range of ignition source geometries and energies is representative of those encountered with known ignition sources of underground coal mine explosions. These include friction, electric arcs, welding, smoking and explosives (Nagy, 1981).

4.12.4 Coal particle size

In previous work (Amyotte et al., 1991a and 1991b), the coal particle sizes were compared to those for colliery samples that had been collected and analyzed by CBDC. Because comparable size distributions were used in the current work, the following comments can be made. The larger size fractions (Prince 1 and Phalen 1) are representative of finer mine sizes. The usefulness of the smaller size fractions (Prince 2 and Phalen 2) lies in showing some of the effects of generating even finer coal dusts. Further support for the use of fine size fractions in laboratory testing is given by Sapko et al. (1989). Their review paper on prevention and suppression of coal mine explosions indicates that the coal dust being generated at present is finer than in earlier years, and that float coal dust is the most dangerous in terms of explosibility.

4.12.5 Coal ash content

The present work was conducted using channel samples of coal (i.e., samples from the mine face). Because of this, the ash contents were less than half of those for the run-of-mine coal samples that were used in previous work (Amyotte et al., 1991a and 1991b). Ash contents of about 7% for the Prince samples and about 14% for the Phalen samples are considered to be representative values.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the main findings of this work are summarized and recommendations arising from the work are given.

5.1 Summary of Conclusions

The principal conclusions which have been drawn from this study are as follows:

(1) The apparent lean flammability limit of coal dust/air mixtures decreases with increasing ignition energy. The decrease is rapid at low energies, with an approach to an asymptotic value of the lean limit at high energies. It is this asymptotic value which represents the true lean flammability limit.

(2) A stored ignition energy of 5 kJ is suitable for measuring true lean limits in the vessel used in this study and with the specified test conditions and limit criteria.

(3) Spark ignition of a coal dust/air mixture is strongly dependent on the turbulence intensity in the dust cloud at the time of attempted ignition.

(4) The apparent lean flammability limit at a given ignition energy is decreased by the presence of methane, by a reduction in mass mean diameter of the parent coal, and by an increase in coal volatile content.

(5) The lowering of the lean limit with methane admixture is more pronounced at lower ignition energies than at higher energies. This influence at low ignition energy is greater for larger particle sizes than for smaller sizes, and for lower volatility coals than for higher volatility coals.

(6) Similarly, the lowering of the lean limit with a reduction in coal particle size is more pronounced at lower ignition energies than at higher energies. This influence at low ignition energy is greater in the absence rather than the presence of methane, and for lower volatility coals than for higher volatility coals.

(7) The lowering of the lean limit with an increase in coal volatile content is also more pronounced at lower ignition energies than at higher energies. This influence at low ignition energy is greater in the absence rather than the presence of methane, and for larger particle sizes than for smaller sizes.

(8) The ignitability of a coal dust/air mixture is enhanced by the presence of methane, by a reduction in mass mean diameter, and by an increase in coal volatile content. In other words, ignition of a given coal dust concentration is attainable with lower energies when any of these three conditions is satisfied.

(9) With respect to explosion inerting levels, limestone, dolomite and magnesite appear to be of similar effectiveness.

(10) The particle size of a particular rock dust has a significant effect on the amount required for inerting, with finer size rock dusts being more effective in explosion suppression.

5.2 Recommendations for Further Work

Based on the experience gained and conclusions drawn from this study, we recommend that the following work would be of value in better understanding the coal dust explosion hazard:

(1) Experiments to investigate the upper or rich flammability limit for coal dust. Some researchers claim there is no rich limit; others say there is, but we simply cannot measure it because of the difficulty of uniformly dispersing large quantities of coal dust. Few studies have been conducted on this topic, which may have some practical value.

(2) Inerting tests at coal dust concentrations other than 0.5 kg/m^3, to examine inerting requirements over a range of hazardous concentrations.

(3) Further inerting tests with magnesite. Even though magnesite does not appear to be any more effective in explosion suppression than limestone or dolomite, the economics of its use may be attractive.

(4) Further inerting tests with different size rock dusts. Such a study could include an evaluation of the benefit-to-cost ratio of producing fine sizes of rock dust.

(5) Inerting tests with different energy ignitors. Such a study would be similar in practical application and scope to the current investigation of effects of ignition energy on the apparent lean flammability limit.

REFERENCES

Abrahamsen, A.R., "The U.K. Approach to Dust Explosibility Assessment and its Relevance to Explosion Prevention and Protection", in "Industrial Dust Explosions", ASTM STP 958, K.L. Cashdollar and M. Hertzberg, Eds., American Society for Testing and Materials, Philadelphia (1987), pp. 60-73.

Alameddin, A.N. and S.T. Luzik, "Coal Dust Explosions in the Cement Industry", in "Industrial Dust Explosions", ASTM STP 958, K.L. Cashdollar and M. Hertzberg, Eds., American Society for Testing and Materials, Philadelphia (1987), pp. 217-233.

Amyotte, P.R., S. Chippett and M.J. Pegg, "Effects of Turbulence on Dust Explosions", Prog. Energy Combust. Sci. **14**, 293-310 (1988).

Amyotte, P.R., K.J. Mintz, M.J. Pegg, Y.H. Sun and K.I. Wilkie, "Laboratory Investigation of the Dust Explosibility Characteristics of Three Nova Scotia Coals", J. Loss Prev. Process Ind. **4**, 102-109 (1991a).

Amyotte, P.R., K.J. Mintz, M.J. Pegg, Y.H. Sun and K.I. Wilkie, "Effects of Methane Admixture, Particle Size and Volatile Content on the Dolomite Inerting Requirements of Coal Dust", J. Haz. Mtls. **in press** (1991b).

Cashdollar, K.L. and M. Hertzberg, "20-L Explosibility Test Chamber for Dusts and Gases", Rev. Sci. Instrum. **56**, 596-602 (1985).

Cashdollar, K.L. and M. Hertzberg, Eds., "Industrial Dust Explosions", ASTM STP 958, American Society for Testing and Materials, Philadelphia (1987).

Cashdollar, K.L. and M. Hertzberg, "Laboratory Study of Rock Dust Inerting Requirements: Effects of Coal Volatility, Particle Size and Methane Addition", Proc. 23rd Int. Conf. of Safety in Mines Research Institutes, Washington, D.C. (1989), pp. 965-975.

Cashdollar, K.L., M.J. Sapko, E.S. Weiss and M. Hertzberg, "Laboratory and Mine Dust Explosion Research at the Bureau of Mines" in "Industrial Dust Explosions", ASTM STP 958, K.L. Cashdollar and M. Hertzberg, Eds., American Society for Testing and Materials, Philadelphia (1987), pp. 107-123.

Chippett, S. and L.G. Britton, "A Method for Characterizing Dust Deflagration Behavior for Application to Vent Relief Design", Particulate Sci. Technol. **3**, 159-177 (1985).

Dixon-Lewis, G., D. Bradley and S. El-Din Habik, "Burning of Coal and Organic Dusts in Air", Archivum Combustionis **7**, 85-98 (1987).

Foniok, R., "Hybrid Dispersive Mixtures and Inertized Mixtures of Coal Dust: Explosiveness and Ignitability", Staub-Reinhalt. Luft **45**, 151-154 (1985).

Hertzberg, M., K.L. Cashdollar, C.P. Lazzara and A.C. Smith, "Inhibition and Extinction of Coal Dust and Methane Explosions", RI 8708, U.S. Bureau of Mines, Pittsburgh (1982).

Hertzberg, M., K.L. Cashdollar and I.A. Zlochower, "Flammability Limit Measurements for Dusts and Gases: Ignition Energy Requirements and Pressure Dependences", 21st Symp. (Int.) Combust., The Combustion Institute, Pittsburgh (1986a), pp. 303-313.

Hertzberg, M., I.A. Zlochower and K.L. Cashdollar, "Volatility Model for Coal Dust Flame Propagation and Extinguishment", 21st Symp. (Int.) Combust., The Combustion Institute, Pittsburgh (1986b), pp. 325-333.

Kauffman, C.W., "Recent Dust Explosion Experiences in the U.S. Grain Industry", in "Industrial Dust Explosions", ASTM STP 958, K.L. Cashdollar and M. Hertzberg, Eds., American Society for Testing and Materials, Philadelphia (1987), pp. 243-264.

Mintz, K.J., "The Explosibility of Three Canadian Coals", MRL 89-50 (TR), CANMET, EMR Canada (1989).

Nagy, J., "The Explosion Hazard in Mining", IR 1119, U.S. Bureau of Mines, Pittsburgh (1981).

Sapko, M.J., N.B. Greninger and R.W. Watson, "Review Paper: Prevention and Suppression of Coal Mine Explosions", Proc. 23rd Int. Conf. of Safety in Mines Research Institutes, Washington, D.C. (11-15 Sept., 1989), pp. 791-806.

Swift, I., "Developments in Dust Explosibility Testing: The Effect of Test Variables" in "Fuel-Air Explosions", J.H.S. Lee and C.M. Guirao, Eds., University of Waterloo Press, Ontario (1982), pp. 375-403.